Reliable Massively Parallel Symbolic Computing:
Fault Tolerance for a Distributed Haskell

by

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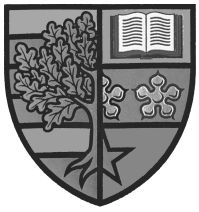
Heriot Watt University



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Abstract

As the number of cores in manycore systems grows exponentially, the number of failures is also predicted to grow exponentially. Hence massively parallel computations must be able to tolerate faults. Moreover new approaches to language design and system architecture are needed to address the resilience of massively parallel heterogeneous architectures.

Symbolic computation has underpinned key advances in Mathematics and Computer Science, for example in number theory, cryptography, and coding theory. Computer algebra software systems facilitate symbolic mathematics. Developing these at scale has its own distinctive set of challenges, as symbolic algorithms tend to employ complex irregular data and control structures. SymGridParII is a middleware for parallel symbolic computing on massively parallel High Performance Computing platforms. A key element of SymGridParII is a domain specific language (DSL) called Haskell Distributed Parallel Haskell (HdpH). It is explicitly designed for scalable distributed-memory parallelism, and employs work stealing to load balance dynamically generated irregular task sizes.

To investigate providing scalable fault tolerant symbolic computation we design, implement and evaluate a reliable version of HdpH, HdpH-RS. Its reliable scheduler detects and handles faults, using task replication as a key recovery strategy. The scheduler supports load balancing with a fault tolerant work stealing protocol. The reliable scheduler is invoked with two fault tolerance primitives for implicit and explicit work placement, and 10 fault tolerant parallel skeletons that encapsulate common parallel programming patterns. The user is oblivious to many failures, they are instead handled by the scheduler.

An operational semantics describes small-step reductions on states. A simple abstract machine for scheduling transitions and task evaluation is presented. It defines the semantics of supervised futures, and the transition rules for recovering tasks in the presence of failure. The transition rules are demonstrated with a fault-free execution, and three executions that recover from faults.

The fault tolerant work stealing has been abstracted in to a Promela model. The SPIN model checker is used to exhaustively search the intersection of states in this automaton to validate a key resiliency property of the protocol. It asserts that an initially empty supervised future on the supervisor node will eventually be full in the presence of all possible combinations of failures.

The performance of HdpH-RS is measured using five benchmarks. Supervised scheduling achieves a speedup of 757 with explicit task placement and 340 with lazy work stealing when executing Summatory Liouville up to 1400 cores of a HPC architecture. Moreover, supervision overheads are consistently low scaling up to 1400 cores. Low recovery overheads are observed in the presence of frequent failure when lazy on-demand work stealing is used. A Chaos Monkey mechanism has been developed for stress testing resiliency with random failure combinations. All unit tests pass in the presence of random failure, terminating with the expected results.

Dedication

To Mum and Dad.

Acknowledgements

Foremost, I would like to express my deepest thanks to my two supervisors, Professor Phil Trinder and Dr Patrick Maier. Their patience, encouragement, and immense knowledge were key motivations throughout my PhD. They carry out their research with an objective and principled approach to computer science. They persuasively conveyed an interest in my work, and I am grateful for my inclusion in their HPC-GAP project.

Phil has been my supervisor and guiding beacon through four years of computer science MEng and PhD research. I am truly thankful for his steadfast integrity, and selfless dedication to both my personal and academic development. I cannot think of a better supervisor to have. Patrick is a mentor and friend, from whom I have learnt the vital skill of disciplined critical thinking. His forensic scrutiny of my technical writing has been invaluable. He has always found the time to propose consistently excellent improvements. I owe a great debt of gratitude to Phil and Patrick.

I would like to thank Professor Greg Michaelson for offering thorough and excellent feedback on an earlier version of this thesis. In addition, a thank you to Dr Gudmund Grov. Gudmund gave feedback on Chapter 4 of this thesis, and suggested generality improvements to my model checking abstraction of HdpH-RS.

A special mention for Dr Edsko de Vries of Well Typed, for our insightful and detailed discussions about network transport design. Furthermore, Edsko engineered the network abstraction layer on which the fault detecting component of HdpH-RS is built.

I thank the computing officers at Heriot-Watt University and the Edinburgh Parallel Computing Centre for their support and hardware access for the performance evaluation of HdpH-RS.

Contents

Chapter 1

Introduction

1.1 Context

The manycore revolution is steadily increasing the performance and size of massively parallel systems, to the point where system reliability becomes a pressing concern. Therefore, massively parallel compute jobs must be able to tolerate *failures*. Research in to High Performance Computing (HPC) spans many areas including language design and implementation, low latency network protocols and parallel hardware. Popular languages for writing HPC applications include Fortran or C with the Message Passing Interface (MPI). New approaches to language design and system architecture are needed to address the growing issue of massively parallel heterogeneous architectures, where processing capability is non-uniform and failure is increasingly common.

Symbolic computation has underpinned key advances in Mathematics and Computer Science. Developing computer algebra systems at scale has its own distinctive set of challenges, for example how to coordinate symbolic applications that exhibit highly irregular parallelism. The HPC-GAP project aims to coordinate symbolic computations in architectures with 10^6 cores [135]. At that scale, systems are heterogeneous and exhibit non-uniform communication latency's, and failures are a real issue. SymGridParII is a middleware that has been designed for scaling computer algebra programs onto massively parallel HPC platforms [112].

A core element of SymGridParII is a domain specific language (DSL) called Haskell Distributed Parallel Haskell (HdpH). It supports both implicit and explicit parallelism. The design of HdpH was informed by the need for reliability, and the language has the potential for fault tolerance. To investigate providing scalable fault tolerant symbolic computation this thesis presents the design, implementation and evaluation of a **R**eliable **S**cheduling version of HdpH, HdpH-**RS**. It adds two new fault tolerant primitives and 10

fault tolerant algorithmic skeletons. A reliable scheduler has been designed and implemented to support these primitives, and its operational semantics are given. The SPIN model checker has been used to verify a key fault tolerance property of the underlying work stealing protocol.

1.2 Contributions

The thesis makes the following research contributions:

1. **A critical review of fault tolerance in distributed systems**. This covers existing approaches to handling failures at various levels including fault tolerant communication layers, checkpointing and rollback, task and data replication, and fault tolerant algorithms (Chapter 2).

2. **A supervised workpool as a software reliability mechanism** [164]. The supervised fault tolerant workpool hides task scheduling, failure detection and task replication from the programmer. The fault detection and task replication techniques that support supervised workpools are prototypes for HdpH-RS mechanisms. Some benchmarks show low supervision overheads of between 2% and 7% in the absence of faults. Increased runtimes are between 8% and 10%, attributed to failure detection latency and task replication, when 1 node fails in a 10 node architecture (Appendix A.1).

3. **The design of fault tolerant language HdpH extensions**. The HdpH-RS primitives `supervisedSpawn` and `supervisedSpawnAt` provide fault tolerance by invoking supervised task scheduling. Their inception motivated the addition of `spawn` and `spawnAt` to HdpH [113]. The APIs of the original and fault tolerant primitives are identical, allowing the programmer to trivially opt-in to fault tolerant scheduling (Section 3.3.2).

4. **The design of a fault tolerant distributed scheduler**. To support the HdpH-RS primitives, a fault tolerant scheduler has been developed. The reliable scheduler algorithm is designed to support work stealing whilst tolerating random loss of single and simultaneous node failures. It supervises the location of supervised tasks, using replication as a recovery technique. Task replication is restricted to expressions with idempotent side effects i.e. side effects whose repetition cannot be observed. Failures are encapsulated with isolated heaps for each HdpH-RS node, so the loss of one node does not damage other nodes (Section 3.5).

5. **An operational semantics for HdpH-RS**. The operational semantics for HdpH-RS extends that of HdpH, providing small-step reduction on states of a simple abstract machine. They provide a concise and unambiguous description of the scheduling transitions in the absence and presence of failure, and the states of supervised sparks and supervised futures. The transition rules are demonstrated with one fault-free execution, and three executions that recover and evaluate task replicas in the presence of faults (Section 3.4).

6. **A validation of the fault tolerant distributed scheduler with the SPIN model checker**. The work stealing scheduling algorithm is abstracted in to a Promela model and is formally verified with the SPIN model checker. Whilst the model is an abstraction, it does model all failure combinations that may occur real architectures on which HdpH-RS could be deployed. The abstraction has an immortal supervising node and three mortal thieving nodes competing for a spark with the work stealing protocol. Any node holding a task replica can write to a future on the supervisor node. A key resiliency property of the model is expressed using linear temporal logic, stipulating that the initially empty supervised future on the supervisor node is eventually full despite node failures. The work stealing routines on the supervisor and three thieves are translated in to a finite automaton. The SPIN model checker is used to exhaustively search the model's state space to validate that the reliability property holds on all reachable states. This it does having searched approximately 8.22 million states of the HdpH-RS fishing protocol, at a reachable depth of 124 transitions (Chapter 4).

7. **The implementation of the HdpH-RS fault tolerant primitives and reliable scheduler**. The implementation of the spawn family of primitives and supervised futures are described. On top of the fault tolerant `supervisedSpawn` and `supervisedSpawnAt` primitives, 10 algorithmic skeletons have been produced that provide high level fault tolerant parallel patterns of computation. All load-balancing and task recovery is hidden from the programmer. The fault tolerant spawn primitives honour the small-step operational semantics, and the reliable scheduler is an implementation of the verified Promela model. In extending HdpH, one module is added for the fault tolerant strategies, and 14 modules are modified. This amounts to an additional 1271 lines of Haskell code in HdpH-RS, an increase of 52%. The increase is attributed to fault detection, fault recovery and task supervision code (Chapter 5).

8. **An evaluation of fault tolerant scheduling performance**. The fault tolerant

HdpH-RS primitives are used to implement five benchmarks. Runtimes and overheads are reported, both in the presence and absence of faults. The benchmarks are executed on a 256 core Beowulf cluster [122] and on 1400 cores of HECToR [58], a national UK compute resource. The task supervision overheads are low at all scales up to 1400 cores. The scalability of the HdpH-RS scheduler design is demonstrated on massively parallel architectures using both flat and hierarchically nested supervision. Flat supervised scheduling achieves a speedup of 757 with explicit task placement and 340 with lazy work stealing when executing Summatory Liouville on HECToR using 1400 cores. Hierarchically nested supervised scheduling achieves a speedup of 89 with explicit task placement when executing Mandelbrot on HECToR using 560 cores.

A Chaos Monkey failure injection mechanism [82] is built-in to the reliable scheduler to simulate random node loss. A suite of eight unit tests are used to assess the resilience of HdpH-RS. All unit tests pass in the presence of random failures on the Beowulf cluster. Executions in the presence of random failure show that lazy on-demand scheduling is more suitable when failure is the common case, not the exception (Chapter 6).

9. **Other contributions** A new fault detecting transport layer has been implemented for HdpH and HdpH-RS. This was collaborative work with members of the Haskell community, including code and testing contributions of a new network transport API for distributed Haskells. (Section 5.5). In the domain of reliable distributed computing, two related papers were produced. The first [163] compares three high level MapReduce query languages for performance and expressivity. The other [162] compares the two programming models MapReduce and Fork/Join.

1.3 Authorship & Collaboration

1.3.1 Authorship

This thesis is closely based on the work reported in the following papers:

- **Supervised Workpools for Reliable Massively Parallel Computing** [164]. *Trends in Functional Programming*, 13th International Symposium, TFP 2012, St Andrews, UK. Springer. With Phil Trinder and Patrick Maier. This paper presents the supervised workpool described in Appendix A.1. The fault detection and task replication techniques that support supervised workpools is a reliable computation prototype for HdpH-RS.

- **Reliable Scalable Symbolic Computation: The Design of SymGridPar2** [112]. 28th *ACM Symposium On Applied Computing*, SAC 2013, Coimbra, Portugal. ACM Press. With Phil Trinder and Patrick Maier. The author contributed the fault detection, fault recovery and fault tolerant algorithmic skeleton designs for HdpH-RS. Supervision and recovery overheads for the Summatory Liouville application using the supervised workpool were presented.

- **Reliable Scalable Symbolic Computation: The Design of SymGridPar2** [113]. Submitted to Computer Languages, Systems and Structures. *Special Issue*. Revised Selected Papers from 28th ACM Symposium On Applied Computing 2013. With Phil Trinder and Patrick Maier. The SAC 2013 publication was extended with a more extensive discussion on SymGridParII fault tolerance. The HdpH-RS designs for task tracking, task duplication, simultaneous failure and a fault tolerant work stealing protocol were included.

Most of the work reported in the thesis is primarily my own, with specific contributions as follows. The SPIN model checking in Chapter 4 is my own work with some contribution from Gudmund Grov. The HdpH-RS operational semantics in Chapter 3 extends the HdpH operational semantics developed by Patrick Maier.

1.3.2 Collaboration

Throughout the work undertaken for this thesis, the author collaborated with numerous development communities, in addition to the the HPC-GAP project team [135].

- *Collaboration with Edsko De Vries, Duncan Coutts and Jeff Epstein* on the development of a network abstraction layer for distributed Haskells [44]. The failure semantics for this transport layer were discussed [48], and HdpH-RS was used as the first real-world case study to uncover and resolve numerous race conditions [47] in the TCP implementation of the transport API.

- *Collaboration with Scott Atchley*, the technical lead on the Common Communications Interface (CCI). The author explored the adoption of the TCP implementation of CCI for HdpH-RS. This work uncovered a bug in the CCI TCP implementation [9] that was later fixed.

- *Collaboration with Tim Watson*, the developer of the CloudHaskell Platform, which aims to mirror Erlang OTP in CloudHaskell. The author uncovered a bug in the `Async` API, and provided a test case [159].

- *Collaboration with Morten Olsen Lysgaard* on a distributed hash table (DHT) for CloudHaskell. The author ported this DHT to CloudHaskell 2.0 (Section 2.4.2) [160].

- *Collaboration with Ryan Newton* on the testing of a ChaseLev [34] work stealing deque for Haskell, developed by Ryan and Edward Kmett. The author uncovered a bug [158] in the `atomic-primops` library [127] when used with TemplateHaskell for explicit closure creation in HdpH. This was identified as a GHC bug, and was fixed in the GHC 7.8 release [126].

Chapter 2

Related Work

This chapter introduces dependable distributed system concepts, fault tolerance and causes of failures. Fault tolerance has been built-in to different domains of distributed computing, including cloud computing, high performance computing, and mobile computing.

Section 2.1 classifies the types of dependable systems and the trade-offs between availability and performance. Section 2.2 outlines a terminology of reliability and fault tolerance concepts that is adopted throughout the thesis. It begins with failure forecasts as architecture trends illustrate a growing need for tolerating faults. Existing fault tolerant mechanisms are described, followed by a summary of a well known implementation of each (Section 2.3). Most existing fault tolerant approaches in distributed architectures follow a checkpointing and rollback-recovery approach, and new opportunities are being explored as alternative and more scalable possibilities.

This chapter ends with a review of distributed Haskell technologies, setting the context for the HdpH-RS design and implementation. Section 2.4 introduces CloudHaskell, a domain specific language for distributed programming in Haskell. Section 2.5 introduces HdpH in detail, the realisation of SymGridParII — a middleware for parallel distributed computing.

2.1 Dependability of Distributed Systems

> "Dependability is defined as that property of a computer system such that reliance can justifiably be placed on the service it delivers. A given system, operating in some particular environment, may fail in the sense that some other system makes, or could in principle have made, a judgement that the activity or inactivity of the given system constitutes failure." [101]

2.1.1 Distributed Systems Terminology

Developing a dependable computing system calls for a combined utilisation of methods that can be classified in to 4 distinct areas [100]. Fault *avoidance* is the prevention of fault occurrence. Fault *tolerance* provides a service in spite of faults having occurred. The *removal* of errors minimises the presence of latent errors. Errors can be *forecast* through estimating the presence, the creation, and the consequences of errors.

Definitions for availability, reliability, safety and maintainability are given in [101]. *Availability* is the probability that a system will be operational and able to deliver the requested services at any given time . The *reliability* of a system is the probability of failure-free operation over a time period in a given environment. The *safety* of a system is a judgement of the likelihood that the system will cause damage to people or its environment. *Maintainable* systems can be adapted economically to cope with new requirements, with minimal infringement on the reliability of the system. *Dependability* is the ability to avoid failures that are more frequent and more severe than is acceptable.

2.1.2 Dependable Systems

Highly Available Cloud Computing

Cloud computing service providers allow users to rent virtual computers on which to run their own software applications. High availability is achieved with the redundancy of virtual machines hosted on commodity hardware. Cloud computing service quality is promised by providers with *service level agreements* (SLA). An SLA specifies the availability level that is guaranteed and the penalties that the provider will suffer if the SLA is violated. Amazon Elastic Compute Cloud (EC2) is a popular cloud computing provider. The EC2 SLA is:

> AWS will use commercially reasonable efforts to make Amazon EC2 available with an Annual Uptime Percentage of at least 99.95% during the Service Year. In the event Amazon EC2 does not meet the Annual Uptime Percentage commitment, you will be eligible to receive a Service Credit. [4]

Fault Tolerant Critical Systems

Failure occurrence in critical systems can result in significant economic losses, physical damage or threats to human life [153]. The failure in a *mission-critical* system may result in the failure of some goal-directed activity, such as a navigational system for aircraft. A *business-critical* system failure may result in very high costs for the business using that

system, such as a computerised accounting system.

Dependable High Performance Computing

Future HPC architectures will require the simultaneous use and control of millions of processing, storage and networking elements. The success of massively parallel computing will depend on the ability to provide reliability and availability at scale [147]. As HPC systems continue to increase in scale, their mean time between failure (MTBF, described in Section 2.2.1) decreases respectively. The message passing interface (MPI) is the defacto message passing library in HPC applications. These two trends have motivated work on fault tolerant MPI implementations [25]. MPI provides a rigid fault model in which a process fault within a communication group imposes failure to all processes within that communication group. An active research area is fault tolerant MPI programming (Section 2.3.5), though that work has yet to be adopted by the broader HPC community [10].

The current state of practise for fault tolerance in HPC systems is checkpointing and rollback (Section 2.2.3). With the increasing error rates and increasing aggregate memory leaving behind I/O capabilities, the checkpointing approach is becoming less efficient [106]. Proactive fault tolerance avoids failures through preventative measures, such as by migrating processes away from nodes that are about to fail. A proactive framework is described in [106]. It uses environmental monitoring, event logging and resource monitoring to analyse HPC system reliability and avoids faults through preventative actions.

The need for HPC is no longer restricted to numerical computations such as multiplying huge matrices filled with floating point numbers. Many problems from the field of *symbolic computing* can only be tackled with the power provided by parallel computers [18]. In addition to the complexities of irregular parallelism in symbolic computing (Section 2.5), these applications often face extremely long runtimes on HPC platforms. So fault tolerance measures also need to be taken in large scale symbolic computation frameworks.

2.2 Fault Tolerance

2.2.1 Fault Tolerance Terminology

Attributes of Failures

The distinction between *failures*, *errors* and *faults* are made in [13]. These three aspects of fault tolerance construct a *fundamental chain* [13], shown in Figure 2.1. In this chain,

a *failure* is an event that occurs when the system does not deliver a service as expected by its users. A *fault* is a characteristic of software that can lead to a system error. An *error* can lead to an erroneous system state giving a system behaviour that is unexpected by system users.

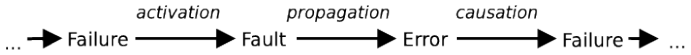


Figure 2.1: Fundamental Chain

Dependability is grouped into three classes in [13], shown in Figure 2.2. The *impairments* to dependability are undesired, but not unexpected. The *means* of dependability are the techniques for providing the ability to deliver a service, and to reach confidence in this ability. The *attributes* enable the properties which are expected from the system, and allow the system quality to be addressed.

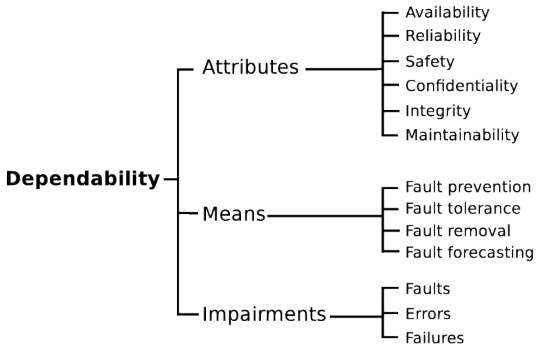


Figure 2.2: Dependability Tree

Attributes of Faults

A fault tolerant system detects and manages faults in such a way that system failure does not occur. Fault *recovery* mechanisms (Section 2.2.3) enable a system to restore its state to a known safe state. This may be achieved by correcting the damaged state with forward error recovery or restoring the system to a previous state using backward error recovery.

The use of verification techniques can be used for fault *detection*. Fault detection mechanisms deal with either *preventative* and *retrospective* faults. An example of a preventative approach is to initialise fault detection prior to committing a state change. If a potentially erroneous state is detected, the state change is not committed. In contrast, a retrospective approach initialises fault detection *after* the system state has changed, to check whether a fault has occurred. If a fault is discovered, an exception is signalled and a repair mechanism is used to recover from the fault.

Faults can occur for many reasons as shown in Figure 2.3. Faults can occur due to improper software techniques, or development incompetence. This includes man made *phenomenological causes*, and development or operational faults during creation. The *capability* or *capacity* of a system may be the cause of faults, e.g. an issue with memory management internally or a lack of capacity for persistent storage.

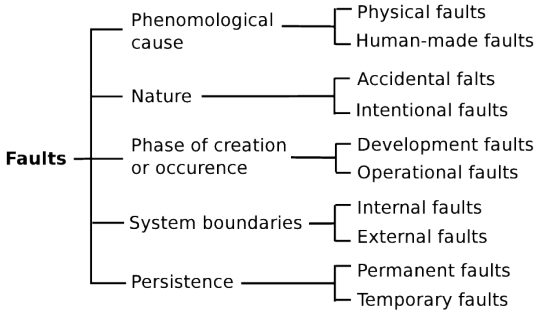


Figure 2.3: Elementary Fault Classes

The availability of a system can be calculated as the probability that it will provide the specified services within required bounds over a specific time interval. A widely used calculation can be used to derive steady-state availability of a system. The mean time between failures (MTBF) and mean time to repair (MTTR) value are used to derive steady-state availability of a system as $\alpha = \frac{MTBF}{MTBF+MTTR}$. Non-repairable systems can fail only once. In systems that do not recover from faults another measure is used, mean time to failure (MTTF), which is the expected time to the failure of a system.

2.2.2 Failure Rates

Unfortunately, obtaining access to failure data from modern large-scale systems is difficult, since such data is often sensitive or classified [145]. Existing studies of failure are often based on only a few months of data [187], and many commonly cited studies on failure analysis stem from the early 1990's, when computer systems were significantly different from today [72]. Failure root causes fall in one of the following five high-level categories: *human* error; *environmental* e.g. power outages or A/C failures; *network* failure, *software* failure, and *hardware* failure [145].

Datasheet and Field Study Data Discrepancies

Studies have been carried out to calculate the MTTF values for specific hardware components. As an example, the MTTF for CPU chips have been calculated at 7 years in [154], and at 11 years in [184]. The MTTF for permanent hard drive failure is investigated in [146]. It compares discrepancies between the datasheet reports for enterprise disks

Rank	HPC		COTS	
	Component	%	Component	%
1	Hard drive	30.6	Power supply	34.8
2	Memory	28.5	Memory	20.1
3	Misc/Unk	14.4	Hard drive	18.1
4	CPU	12.4	Case	11.4
5	PCI motherboard	4.9	Fan	8.0
6	Controller	2.9	CPU	2.0
7	QSW	1.7	SCSI board	0.6
8	Power supply	1.6	NIC card	1.2
9	MLB	1.0	LV power board	0.6
10	SCSI BP	0.3	CPU heatsink	0.6

Table 2.1: Relative frequency of hardware component failure that required replacement

and actual failure logs from field studies in HPC and internet service provider clusters. The authors conclude that large-scale installation field usage differs widely from nominal datasheet MTTF conditions. In particular for five to eight year old drives, field replacement rates were a factor of 30 more than the MTTF datasheet had suggested. The study also reports the relative frequency of failure across all hardware components in HPC and commodity-off-the-shelf (COTS) environments from their field studies, and the results are in Table 2.1.

HECToR Case Study

HECToR (High End Computing Terascale Resource) [58] is a national high-performance computing service for the UK academic community. The service began in 2008, and is expected to operate until 2014. An evaluation of executing HdpH-RS benchmarks on HECToR are in Section 6.4. As of August 2013, it had a theoretical capacity of over 800 Teraflops per second, and over 90,112 processing cores.

Monthly, quarterly and annual HECToR reports are published, detailing time usage, disk usage, failures, MTBF and performance metrics. The following statistics are published in the annual report from January 2012 to January 2013 [79]. The overall MTBF was 732 hours, compared with 586 hours in 2011. There were 12 technology-attributed service failures. This comprised 4 instances of late return to service following scheduled maintenance sessions, 3 PBS batch subsystem related failures, 1 cabinet blower failure, 1 Lustre filesystem failure, 2 HSN failures, and 1 acceptance testing overrun. There were 166 single node failures over the 12 months. The peak was 29 in October 2012, due to a software bug.

2.2.3 Fault Tolerance Mechanisms

There are many fault tolerance approaches in HPC and COTS environments. Faults can be detected, recovered from, and prevented (Section 2.2.3). The tactics for fault tolerance detection, recovery and prevention are shown in Figure 2.4 [149].

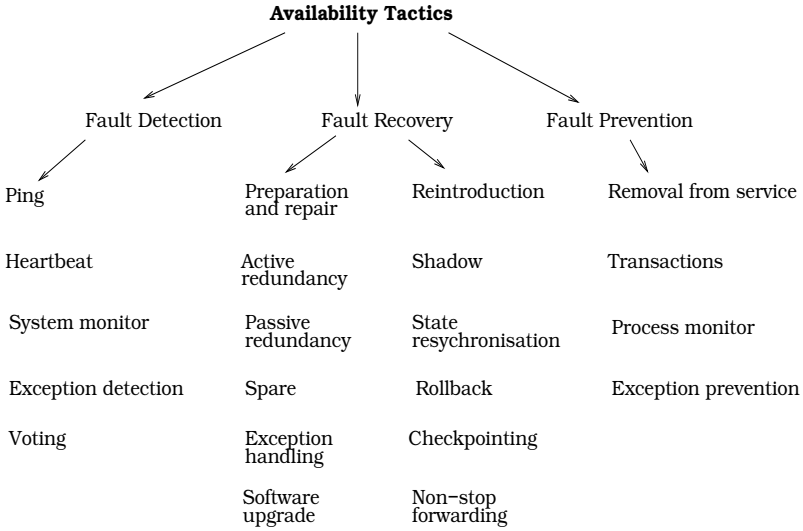


Figure 2.4: Availability Tactics

Fault Detectors

A simple protocol for detecting failure is *ping-pong*. The messages in a ping-pong are shown in Figure 2.5. Process P_i pings P_j once every T time units, and P_j replies each time with a pong message. The failure detection time of a failure is $2T$.

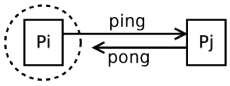


Figure 2.5: Ping-Pong

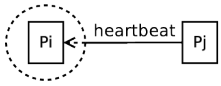


Figure 2.6: Passive Heartbeats

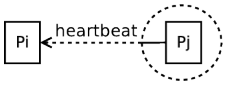


Figure 2.7: Active Heartbeats

An alternative is the *heartbeat* protocol. A *passive* heartbeat protocol is shown in Figure 2.6. In this illustration, P_j sends a heartbeat to P_i every time unit T. The heartbeat contains a sequence number, which is incremented each time. When process P_i receives a heartbeat message, it resets a timer that ticks after T time units. A latency delay α for heartbeat arrival is tolerated. If a heartbeat is not receive within a period of $T + \alpha$, P_j is assumed to have failed. *Active* heartbeats is a variant, shown in Figure 2.7. It can be used in connection oriented transport implementations, when unsuccessful transmission attempts throw exceptions.

Monitors are components that can monitor many parts of a system, such as processors, nodes, and network congestion. They may use heartbeat or ping-pong protocols

to monitor remote components in distributed systems. In message passing distributed systems, *timestamps* can be used to detect or re-order incorrect event sequences. The correctness of programs can be recorded using *condition* monitoring, such as computing checksums, or validating assumptions made during designs processes.

Fault Recovery

Replication Replication is a common fault tolerance recovery strategy (Section 2.3).

> "Replication is a primary means of achieving high availability in fault-tolerant distributed systems. Multicast or group communication is a useful tool for expressing replicated algorithms and constructing highly available systems. But programming language support for replication and group communication is uncommon." [40].

The authors of [2] define three replication strategies: *passive, semi-active* and *active*. In the *passive* approach, the replica task is a backup in case failure occurs. The regular task is executed, and only if fails is the corresponding replica scheduled for re-execution. The *semi-active* approach *eagerly* races the execution of both the regular and replica tasks. The same is true for *active* replication, though this time both results are considered to ensure the results are equal. This is more costly than the *semi-active* approach, as consensus (Section 2.2.4) is required to accept a final value.

A well known use of replication is in MapReduce frameworks (Section 2.3.2), such as Hadoop [183]. It replicates tasks over a distributed runtime system, and data chunks over a distributed filesystem. Data replication for fault tolerance is also common in NoSQL databases and distributed hash tables (Section 2.3.3).

Rollback and Checkpointing Most existing work in fault tolerance for HPC systems is based on checkpointing and rollback recovery. Checkpointing methods [32] are based on periodically saving a global or semi-global state to stable storage.

There are two broad distinctions — *global synchronous* checkpointing systems, and local or *semi-global asynchronous* mechanisms. Global checkpointing simplifies the requirement of satisfying safety guarantees, but is not a scalable solution. Asynchronous checkpointing approaches have potential to scale on larger systems, though encounter difficult challenges such rollback propagation, domino effects , and loss of integrity through incorrect rollback in dependency graphs [59].

Prior work on checkpointing storage for HPC has focused on two areas. The first is node local checkpointing storage, and the second involves centralised techniques that

focus on high-performance parallel systems [125]. The bandwidth between I/O nodes in distributed systems is often regarded as the bottleneck in distributed checkpointing.

Rollback recovery [59] is used when system availability requirements can tolerate the outage of computing systems during recovery. It offers a resource efficient way of tolerating failure, compared to other techniques such as replication or transaction processing [60]. In message passing distributed systems, messages induce interprocess dependencies during failure-free operation. Upon process failure, these dependencies may force some of the processes that did not fail to roll back to a rollback line, which is called *rollback propagation* [59]. Once a good state is reached, process execution resumes.

Log based rollback-recovery [166] combines checkpointing and logging to enable processes to replay their execution after a failure beyond the most recent checkpoint. Log-based recovery generally is not susceptible to the domino effect, thereby allowing the processes to use uncoordinated checkpointing if desired. Three main techniques of logging are *optimistic logging*, *causal logging*, and *pessimistic logging*. *Optimistic* logging assumes that messages are logged, but part of these logs can be lost when a fault occurs. Systems that implement this approach use either a global coherent checkpoint to rollback the entire application, or they assume a small number of fault at one time in the system. *Causal* logging is an optimistic approach, checking and building an event dependency graph to ensure that potential incoherence in the checkpoint will not appear. All processes record their "happened before" activities in an antecedence graph, in addition to the logging of sent messages. Antecedence graphs are asynchronously sent to a stable storage with checkpoints and message logs. When failures occur, all processes are rolled back to their last checkpoints, using antecedence graphs and message logs. Lastly, *pessimistic* logging is a transaction log ensuring that no incoherent state can be reached starting from a local checkpoint of processes, even with an unbounded number of faults.

Other Mechanisms Degrading operations [12] is a tactic that suspends non-critical components in order to keep alive the critical aspects of system functionality. Degradation can reduce or eliminate fault occurrence by gracefully reducing system functionality, rather than causing a complete system failure. Shadowing [17] is used when a previously failed component attempts to rejoin a system. This component will operate in a *shadow mode* for a period of time, during which its behaviour will be monitored for correctness and will repopulate its state incrementally as confidence of its reliability increases.

Retry tactics [75] can be an effective way to recover from transient failures — simply retrying a failed operation may lead to success. Retry strategies have been added to networking protocols in Section 2.3.4, and also to language libraries such as the `gen_server`

abstraction for Erlang in Section 2.3.6.

Fault Prevention

The prevention of faults is a tactic to avoid or minimise fault occurrence. The component removal tactic [68] involves the precautionary removal of a component, *before* failure is detected on it. This may involve resetting a node or a network switch, in order to scrub latent faults such as memory leaks, before the accumulation of faults amounts to failure. This tactic is sometimes referred to as software rejuvenation [86].

Predictive modeling [103] is often used with monitors (Section 2.2.3) to gauge the health of components or to ensure that the system is operating within its nominal operating parameters such as the load on processors or memory, message queue size, and latency of ping-ack responses (Section 2.2.3). As an example, most motherboards contain temperature sensors, which can be accessed via interfaces like ACPI [41], for monitoring nominal operating parameters. Predictive modeling has been used in a fault tolerant MPI [31], which proactively migrates execution from nodes when it is experiencing intermittent failure.

2.2.4 Software Based Fault Tolerance

Distributed Algorithms for Reliable Computing

Algorithmic level fault tolerance is a high level fault tolerance approach. Classic examples include leader election algorithms, consensus through voting and quorums, and smoothing results with probabilistic accuracy bounds.

Leader election algorithms are used to overcome the problem of crashes and link failures in both synchronous and asynchronous distributed systems [66]. They can be used in systems that must overcome master node failure in master/slave architectures. If a previously elected leader fails, a new election procedure can unilaterally identify a new leader.

Consensus is the agreement of a system status by the fault-free segment of a process population in spite of the possible inadvertent or even malicious spread of disinformation by the faulty segment of that population [14]. Processes propose values, and they all eventually agree on one among these values. This problem is at the core of protocols that handle synchronisation, atomic commits, total order broadcasting, and replicated file systems.

Using quorums [115] is one way to enhance the availability and efficiency of replicated data structures. Each quorum can operate on behalf of the system to increase its avail-

ability and performance, while an intersection property guarantees that operations done on distinct quorum preserve consistency [115].

Probabilistic accuracy bounds are used to specify approximation limits on smoothing results when some tasks have been lost due to partial failure. A technique presented in [137] enables computations to survive errors and faults while providing a bound on any resulting output distortion. The fault tolerant approach here is simple: tasks that encounter faults are discarded. By providing probabilistic accuracy bounds on the distortion of the output, the model allows users to confidently accept results in the presence of failure, provided the distortion falls with acceptable bounds.

A non-masking approach to fault tolerance is Algorithm Based Fault Tolerance (ABFT) [85]. The approach consists of computing on data that is encoded with some level of redundancy. If the encoded results drawn from successful computation has enough redundancy, it remains possible to reconstruct the missing parts of the results. The application of this technique is mainly based on the use of parity checksum codes, and is widely used in HPC platforms [139].

> "A system is self-stabilising when, regardless of its initial state, it is guaranteed to arrive at a *legitimate state* in a finite number of steps." – Edsger W. Dijkstra [53]

Self stabilisation [144] provides a non-masking approach to fault tolerance. A self stabilising algorithm converges to some predefined set of *legitimate states* regardless of its initial state. Due to this property, self-stabilising algorithms provide means for tolerating transient faults [69]. Self-stabilising algorithms such as [53] use forward recovery strategies. That is, instead of being externally stopped and rolled-back to a previous correct state, the algorithm continues its execution despite the presence of faults, until the algorithm corrects itself without external influence.

Fault Tolerant Programming Libraries

In the 1980's, programmers often had few alternatives faced with choosing a programming language for writing fault tolerant distributed software [5]. At one end of the spectrum were relatively low-level choices such as C, coupled with a fault tolerance library such as ISIS [16]. The ISIS system transforms abstract type specifications into fault tolerance distributed implementations, while insulating users from the mechanisms used to achieve fault tolerance. The system itself is based on a small set of communication primitives. Whilst such applications may have enjoyed efficient runtime speeds, the approach forced the programmer to deal with the complexities of distributed execution and fault tolerance in a language that is fundamentally sequential.

At the other end of the spectrum were high-level languages specifically intended for constructing fault tolerant application using a given technique, such as Argus [105]. These languages simplified the problems of faults considerably, yet could be overly constraining if the programmer wanted to use fault tolerance techniques other than the one supported by the language.

Another approach is to add language extensions to support fault tolerance. An example is FT-SR [141], an augmentation of the general high-level distributed programming language SR [5], augmented with fault tolerance mechanisms. These include replication, recovery and failure notification. FT-SR was implemented using the x-kernel [87], an Operating System designed for experimenting with communication protocols.

2.3 Classifications of Fault Tolerance Implementations

This section describes examples of fault tolerant distributed software systems. This begins with a case study of a reliability extension to a symbolic computation middleware in Section 2.3.1. The fault tolerance of the MapReduce programming model is described in Section 2.3.2. A discussion on fault tolerant networking protocols is in Section 2.3.4. As MPI is prominently the current defacto standard for message passing in High Performance Computing, Section 2.3.5 details numerous fault tolerant MPI implementations. Supervision and fault recovery tactics in HdpH-RS are influenced by Erlang, described in Sections 2.3.6 and 2.3.7.

2.3.1 Fault Tolerance for DOTS Middleware

A reliability extension to the Distributed Object-Oriented Threads System (DOTS) symbolic computation framework [19] is presented in [18]. DOTS was originally intended for the parallelisation of application belonging to the field of symbolic computation, but it has also been successfully used in other application domains such as computer graphs and computational number theory.

Programming Model

DOTS provides object-oriented asynchronous remote procedure calls services accessible from C++ through a *fork/join* programming API, which also supports thread cancellation. Additionally, it supports object-serialisation for parameter passing. The programming model provides a uniform and high-level programming paradigm over hierarchical

multiprocessor systems. Low level details such as message passing and shared memory threads within a single parallel application are masked from the programmer [18].

Fault Tolerance

The fault tolerance in the reliable extension to DOTS is achieved through asynchronous checkpointing, realised by two orthogonal approaches. The first is *implicit* checkpointing. It is completely hidden from the programmer, and no application code modifications are necessary. The second is *explicit* checkpointing by adding three new API calls, allowing the programmer to explicitly control the granularity needs of the application.

To realise the *implicit* checkpointing approach, *function memoization* [142] is used. A checkpoint consists of a pair containing the argument and the computed result of a thread — whenever a thread has successfully finished its execution, a checkpoint is taken. The checkpointed data is stored in a *history table*. In the case of a restart of a thread, a replay of communication and computation takes place. If the argument of the thread is present in the history table, the result is taken from the table and immediately sent back to the caller. This strategy is feasible whenever the forked function is stateless.

2.3.2 MapReduce

MapReduce is a programming model and an associated implementation for processing and generating large data sets [49]. Programs written in the functional style are automatically parallelisable and can be run on large clusters. Its fault tolerance model make implementations such as Hadoop [183] a popular choice for running on COTS architectures, where failure is more common than on HPC architectures. The use of task re-execution (Section 2.2.3) is the fault tolerance mechanism. Programmers can adopt the MapReduce model directly, or can use higher level data query languages [163].

The MapReduce architecture involves one *master* node, and all other nodes are slave nodes. They are responsible both for executing tasks, and hosting chunks of the MapReduce distributed filesystem. Fault tolerance is achieved by replicating tasks and distributed filesystem chunks, providing both task parallel and data parallel redundancy. A comparison between Hadoop and HdpH-RS is made in Section 5.6.2.

2.3.3 Distributed Datastores

Distributed data structures such as distributed hash tables [28] and NoSQL databases [165] often provide flexible performance and fault tolerance parameters. Optimising one parameter tends to put pressures on others. Brewer's CAP theorem [26] states a trade

off between *consistency*, *availability* and *partition tolerance* — a user can only have two out of three. An important property of a DHT is a degree of their *fault tolerance*, which is the fraction of nodes that can fail without eliminating data or preventing successful routing [96].

NoSQL databases do not require fixed table schemas, and are designed to scale horizontally and manage huge amounts of data. One of the first NoSQL databases was Google's proprietary BigTable [33], and subsequent open source NoSQL databases have emerged including Riak [170]. Riak is a scalable, highly-available, distributed key/value store built using Erlang/OTP (Section 2.3.7). It is resilient to failure through a quorum based eventual consistency model, based on Amazon's Dynamo paper [50].

2.3.4 Fault Tolerant Networking Protocols

There are many APIs for connecting and exchanging data between network peers. In 1981, the Internet Protocol (IP) [132] began the era of ubiquitous networking. When processes on two different computer communicate, the most often do so using the TCP protocol [156]. It offers a convenient bi-directional bytestream interface for communication. It also hides most communication problems from the programmer, such as message losses and message duplicates, overcome using sequence numbers and acknowledgements.

TCP/IP uses the sockets interfaces supported by many Operating Systems. It is the widely used protocol that Internet services rely upon. It has a simple API that provides stream and datagram modes, and is robust to failure. It does not provide the collective communications or one-sided operations that MPI provides.

FT-TCP [3] is an architecture that allows a replicated service to survive crashes without breaking its TCP connections. It is a failover software implementation that wraps the TCP stack to intercept all communication, and is based on message logging.

In the HPC domain, MPI is the dominant interface for inter-process communication [10]. Designed for maximum scalability, MPI has a richer though also more complex API than sockets. The complications of fault tolerant MPI are detailed in Section 2.3.5.

There are numerous highly specialised vendor APIs for distributed network peer communication. Popular examples include Cray Portals [27], IBM's LAPI [150] and Infiniband Verbs [8]. Verbs has support for two-sided and one-sided asynchronous operations, and buffer management is left to the application. Infiniband [107] is a switched fabric communications link commonly used in HPC clusters. It features high throughput, low latency and is designed for scalability.

The performance of each interface varies wildly in terms of speed, portability, robustness and complexity. The design of each balance the trade-off between these performance

	Sockets	MPI	Specialised APIs
Performance	No	Yes	Yes
Scalability	No	Yes	Varies
Portability	Yes	Yes	No
Robustness	**Yes**	**No**	**Varies**
Simplicity	Yes	No	Varies

Table 2.2: Metrics for Network Protocols

metrics, e.g. trading portability for high performance. Table 2.2 lists performance metrics for sockets, MPI and these specialised APIs.

The Common Communication Interface (CCI) [10] aims to address the problem of using these specialised APIs, without having to understand the complexities of each. The goal is to create a relatively simple high-level communication interface with low barriers of adoption, while still providing important features such as scalability, performance, and resiliency for HPC and COTS architectures.

CCI uses connection-oriented semantics for peers to provide fault isolation, meaning that a fault peer only affects that connection and not all communication. Additionally, it also provides flexible reliability and ordering semantics. CCI is an alternative to MPI (Section 2.3.5). If a HPC user needs tag matching and communicators, then MPI is more suitable. If they do not need tag matching and communicators, and their target is a low-latency, high-throughput network with support for fault tolerance, then CCI may be more suitable.

Fault detection in CCI uses *keepalive* timeouts that prevent a client from connecting to a server, and then disappearing to a server without noticing. If no traffic at all is received on a connection within a timeout period, a keepalive event is raised on that connection. The CCI implementation automatically sends control heartbeats across an inactive connection, to reset the peer's keepalive timer before it times out.

A level up from network protocols, orthogonal implementations target message-oriented middleware. A popular example is ZeroMQ [81], an AMQP [178] interface. It provides patterns of message communication, including publish-subscribe, pipelining and request-reply. Recovery from faults such as network outages and client disconnects are handled within the middleware.

2.3.5 Fault Tolerant MPI

Most scientific applications are written either in C with MPI, or Parallel Fortran [98]. MPI provides both two-sided semantics in MPI-1 [65], and one-sided semantics in MPI-2

[123]. It also provides tag matching and collective operations.

Paradoxically however, fault tolerant MPI programming for users is challenging, and they are often forced to handle faults programmatically. This will become increasingly problematic as MPI is scaled to massively parallel exascale systems as soon as 2015 [62]. The original MPI standards specify very limited features related to reliability and fault tolerance [73]. Based on the early standards, an entire application is shut down when one of the executing processors experiences a failure, as fault handling is per communicator group, and not be peer. The default behaviour in MPI is that any fault will typically bring down the entire communicator.

This section describes several approaches to achieve fault tolerance in MPI programs including the use of checkpointing, modifying the semantics of existing MPI functions to provide more fault-tolerant behaviour, or defining extensions to the MPI specification.

Fault Tolerant MPI Implementations

A typical MPI software stack is shown in Figure 2.8. MPI uses network hardware via network abstraction layers, such as Verbs over Infiniband, or sockets over TCP/IP based Ethernet.

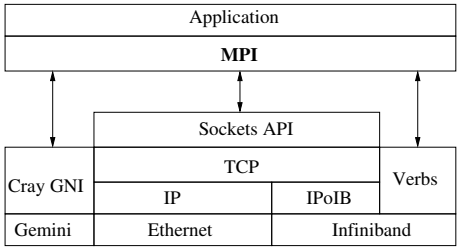


Figure 2.8: MPI Network Stack

Many fault tolerant MPI implementations adopt the checkpointing approach (Section 2.2.3). LAM-MPI [140] provides a variety of fault tolerance mechanisms including an MPI coordinated checkpointing interface. A checkpoint is initiated either by a user or a batch scheduler, which is propagated to all processes in an MPI job.

For the checkpoint and restart components of LAM-MPI, three abstract actions are defined: *checkpoint*, *continue* and *restart*. The *checkpoint* action is invoked when a checkpoint is initiated. Upon receiving checkpoint requests, all the MPI processes interact with each other to ensure a globally consistent state — defined by process states and the state of communication channels. The *continue* action is activated after a successful checkpoint, which may re-establish communication channels if processes have moved from failed nodes to a new node in the system. The *restart* action is invoked after an MPI

process has been restored from a prior checkpoint. This action will almost always need to re-discover its MPI process peers and re-establish communication channels to them.

The MPICH-V [24] environment encompasses a communication library based on MPICH [74], and a runtime environment. MPICH-V provides an automatic volatility tolerant MPI environment based on uncoordinated checkpointing and rollback and distributed message logging. Unlike other checkpointing systems such as LAM-MPI, the checkpointing in MPICH-V is *asynchronous*, avoiding the risk that some nodes may unavailable during a checkpointing routine.

Cocheck [155] is an independent application making an MPI parallel application fault tolerant. Cocheck sits at the runtime level on top of a message passing library, providing a consistency at a level above the message passing system. Cocheck coordinates the application processes checkpoints and flushes the communication channels of the target applications using a Chandy-Lamport's algorithm [52]. The program itself is not aware of checkpointing or rollback routines. The checkpoint and rollback procedures are managed by a centralised coordinator.

FT-MPI [51] takes an alternative approach, by modifying the MPI semantics in order to recover from faults. Upon detecting communication failures, FT-MPI marks the associated node as having a *possible* error. All other nodes involved with that communicator are informed. It extends the MPI communicator states, and default MPI process sates [63].

LA-MPI [11] has numerous fault tolerance features including application checksumming, message re-transmission and automatic message re-routing. The primary motivation for LA-MPI is fault tolerance at the data-link and transport levels. It reliably delivers messages in the presence of I/O bus, network card and wire-transmission errors, and so guarantees delivery of in-flight message after such failures.

2.3.6 Erlang

Erlang is a distributed functional programming language and is becoming a popular solution for developing highly concurrent, distributed soft real-time systems. The Erlang approach to failures is *let it crash and another process will correct the error* [7].

New processes are created with a `spawn` primitive. The return value of a `spawn` call is a process ID (`PID`). One process can monitor another by calling `monitor` on its `PID`. When a process dies, A `DOWN` message is sent to all monitoring processes. For convenience, the function `spawn_monitor` atomically spawns a new process and monitors it. An example of using `spawn_monitor` is shown in Listing 2.1. The `time_bomb/1` function ticks down from N every second. When N reaches 0, the process dies. The `repeat_explosion/2` function

recursively spawns `time_bomb/1` R times, monitoring each process. The execution of `repeat_explosion/2` in Listing 2.2 demonstrates that the death of spawned processes executing `time_bomb/1` does not impact on the program execution.

```
1  -module(ammunition_factory).
2  -export([repeat_explosion/2,time_bomb/1]).
3
4  repeat_explosion(0,_) -> ok;
5  repeat_explosion(R,N) ->
6      {_Pid,_MonitorRef} = spawn_monitor(fun() -> time_bomb(N) end),
7      receive X -> io:format("Message: ~p\n",[X]),
8      repeat_explosion(R-1,N) end.
9
10 time_bomb(0) -> exit("boom!");
11 time_bomb(N) -> timer:sleep(1000), time_bomb(N-1).
```

Listing 2.1: Illustration of Fault Tolerant Erlang using Monitors

```
1> c(ammunition_factory).
{ok,ammunition_factory}
2> ammunition_factory:repeat_explosion(3,1).
Message: {'DOWN',#Ref<0.0.0.60>,process,<0.39.0>,"boom!"}
Message: {'DOWN',#Ref<0.0.0.62>,process,<0.40.0>,"boom!"}
Message: {'DOWN',#Ref<0.0.0.64>,process,<0.41.0>,"boom!"}
ok
```

Listing 2.2: Execution of `repeat_explosion/2 from Listing 2.1`

The second way to handle faults in Erlang is by linking processes. Bidirectional links are created between processes with the `link` function. As with `monitor`, a `PID` argument is used to identify the process being linked to. For convenience, the function `spawn_link` atomically spawns a new process and creates a bidirectional link to it. Erlang OTP fault tolerance (Section 2.3.7) is implemented in a simple way using the nature of these links.

2.3.7 Process Supervision in Erlang OTP

Erlang OTP [108] provides library modules that implement common concurrent design patterns. Behind the scenes, and without the programmer having to be aware of it, the library modules ensure that errors and specific cases are handled in a consistent way. OTP behaviours are a formalisation of process design patterns. These library modules do all of the generic process work and error handling. The application specific user code is placed in a separate module and called through a set of predefined callback functions.

OTP behaviours include *worker* processes, which do the actual processing. Supervisors monitor their children, both workers and other supervisors — creating a *supervision tree*, shown in Figure 2.9.

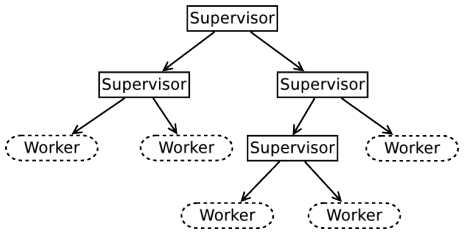


Figure 2.9: Supervision Trees in Erlang OTP

When constructing an OTP supervision tree, the programmer defines processes with supervisor and child specifications. The supervisor specification describes how the supervisor should react when a child terminates. An `AllowedRestarts` parameter specifies the maximum number of abnormal terminations the supervisor is allowed to handle in `MaxSeconds` seconds. A `RestartStrategy` parameter determines how other children are affected if one of their siblings terminates. The child specifications provide the supervisor with the properties of each of its children, including instructions on how to start it. A `Restart` parameter defines the restart strategy for a child — either transient, temporary or permanent.

2.4 CloudHaskell

CloudHaskell [61] emulates Erlang's approach of isolated process memory with explicit message passing, and provides process linking. It explicitly targets distributed-memory systems and it implements all parallelism extensions entirely in Haskell. No extensions to the GHC [93] runtime system are needed . CloudHaskell inherits the language features of Haskell, including purity, types, and monads, as well as the multi-paradigm concurrency models in Haskell. CloudHaskell includes a mechanism for serialising function closures, enabling higher order functions to be used in distributed computing environments.

2.4.1 Fault Tolerance in CloudHaskell

Fault tolerance in CloudHaskell is based on ideas from Erlang (Section 2.3.6). If a monitored process terminates, the monitoring process will be notified. Ascertaining the origin of the failure and recover from it are left to the application. The process linking and monitoring in CloudHaskell is shown in Listing 2.3. As CloudHaskell has borrowed the fault tolerance ideas from Erlang, the `repeat_explosion/2` Erlang example in Listing

2.1 could similarly be constructed with CloudHaskell using `spawnMonitor` in 2.3. At a higher level, another fault tolerance abstraction is redundant distributed data structures. The author has contributed [160] to the development of a fault tolerant Chord-based distributed hash table in CloudHaskell.

```
1  -- * Monitoring and linking
2  link       :: ProcessId → Process ()
3  monitor    :: ProcessId → Process MonitorRef
4
5  -- * Advanced monitoring
6  spawnLink       :: NodeId → Closure (Process ()) → Process ProcessId
7  spawnMonitor    :: NodeId → Closure (Process ()) → Process (ProcessId, MonitorRef)
8  spawnSupervised :: NodeId → Closure (Process ()) → Process (ProcessId, MonitorRef)
```

Listing 2.3: CloudHaskell Fault Tolerant Primitives

2.4.2 CloudHaskell 2.0

Following on from the release of CloudHaskell as reported in [61], a second version of CloudHaskell was developed [42], keeping the APIs largely the same. It was engineered by the WellTyped company [182], and has since been maintained through a community effort.

The CloudHaskell 2.0 framework is de-coupled into multiple layers, separating the process layer, transport layer, and transport implementations. The network transport layer is inspired by the CCI software stack, separating the transport API from protocol implementations. The software stack as illustrated in Figure 2.10 is designed to encourage additional middlewares other than CloudHaskell (e.g. HdpH) for distributed computing, and for alternative network layer implementations other than TCP (Section 2.3.4).

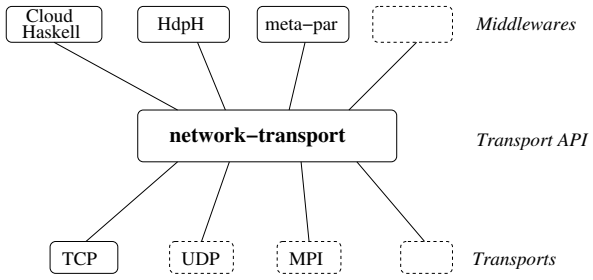


Figure 2.10: Distributed Haskell Software Layers

2.5 SymGridParII

Symbolic computation is an important area of both Mathematics and Computer Science, with many large computations that would benefit from parallel execution. Symbolic computations are, however, challenging to parallelise as they have complex data and control structures, and both dynamic and highly irregular parallelism. In contrast to many of the numerical problems that are common in HPC applications, symbolic computation cannot easily be partitioned into many subproblems of similar type and complexity.

The SymGridPar (SGP) framework [104] was developed to address these challenges on small-scale parallel architectures. However, the multicore revolution means that the number of cores and the number of failures are growing exponentially, and that the communication topology is becoming increasingly complex. Hence an improved parallel symbolic computation framework is required. SymGridParII is a successor to SGP that is designed to provide scalability onto 10^6 cores, and hence also provide fault tolerance.

The main goal in developing SGPII [112] as a successor to SGP is scaling symbolic computation to architectures with 10^6 cores. This scale necessitates a number of further design goals, one of which is *fault tolerance*, to cope with increasingly frequent component failures (Section 2.2.2).

2.6 HdpH

The realisation of SGPII is Haskell Distributed Parallel Haskell (HdpH). The language is a shallowly embedded parallel extension of Haskell that supports high-level implicit and explicit parallelism.

To handle the complex nature of symbolic applications, HdpH supports dynamic and irregular parallelism. Task placement in SGPII should avoid explicit choice wherever possible. Instead, choice should be semi-explicit, so the programmer decides which tasks are suitable for parallel execution and possibly at what distance from the current node they should be executed. HdpH therefore provides high-level *semi-explicit* parallelism. The programmer is not required to explicitly place tasks on specific node, instead idle nodes seek work automatically. The HdpH implementation continuously manages load, ensuring that all nodes are utilised effectively.

2.6.1 HdpH Language Design

HdpH supports two parallel programming models. The first is a continuation passing style [167], when the language primitives are used directly. This supports a dataflow

programming style. The second programming model is through the use of higher order parallel skeletons. Algorithmic skeletons have been developed on top of the HdpH primitives to provide higher order parallel skeletons, inspired by the *Algorithms + Skeletons = Parallelism* paper [171].

The HdpH language is strongly influenced by two Haskell libraries, that lift functionality normally provided by a low-level RTS to the Haskell level.

Par Monad [118] A shallowly embedded domain specific language (DSL) for deterministic shared-memory parallelism. The HdpH primitives extend the `Par` monad for *distributed memory* parallelism.

Closure serialisation in CloudHaskell HdpH extends the closure serialisation techniques from CloudHaskell (Section 2.4) to support polymorphic closure transformation, which is used to implement high-level coordination abstractions.

2.6.2 HdpH Primitives

The API in Figure 2.4 expose scheduling primitives for both *shared* and *distributed* memory parallelism. The shared memory primitives are inherited from the `Par` monad. The `Par` type constructor is a monad for encapsulating a parallel computation. To communicate the results of computation (and to block waiting for their availability), threads employ `IVar`s, which are essentially mutable variables that are writable exactly once. A user can create an IVar with `new`, write to them with `put`, and blocking read from them with `get`.

The basic primitive for shared memory scheduling is `fork`, which forks a new thread and returns nothing. The two primitives for distributed memory parallelism are `spark` and `pushTo`. The former operates much like `fork`, generating a computation that *may* be executed on another node. The `pushTo` primitive is similar except that it eagerly pushed a computation to a target node, where it eagerly unwrapped from its closured form and executed. In contrast to this scheduling strategy, `spark` just stores its argument in a local *sparkpool*, where it sits waiting to be distributed, or scheduled by an on-demand work-stealing scheduler, described in Section 2.6.4. Closures are constructed with the `mkClosure` function. It safely converts a quoted thunk i.e. an expression in Template Haskell's quotation brackets `[|..|]` into a quoted `Closure` [114].

2.6.3 Programming Example with HdpH

A HdpH implementation of the Fibonacci micro-benchmark is shown in Listing 2.5. It uses `spark` to allow the lazy work stealing HdpH scheduling to (maybe) evaluate `fib n-1`,

```
1  -- * Types
2  type Par
3  data NodeId
4  data IVar a
5  data GIVar a
6
7  -- * Locality
8  myNode   :: Par NodeId
9  allNodes :: Par [NodeId]
10
11 -- * Scheduling
12 fork   :: Par () → Par ()
13 spark  :: Closure (Par ()) → Par ()
14 pushTo :: Closure (Par ()) → NodeId → Par ()
15
16 -- * Closure construction
17 mkClosure :: ExpQ → ExpQ
18
19 -- * IVar Operations
20 new :: Par (IVar a)
21 put :: IVar a → a → Par ()
22 get :: IVar a → Par a
23 tryGet :: IVar a → Par (Maybe a)
24 probe  :: IVar a → Par Bool
25 glob :: IVar (Closure a)  → Par (GIVar (Closure a))
26 rput :: GIVar (Closure a) → Closure a → Par ()
```

Listing 2.4: HdpH Primitives

`fib n-2`, `fib n-3` etc. . . in parallel.

2.6.4 HdpH Implementation

The HdpH system architecture is shown in Figure 2.11. Each node runs several thread schedulers, typically one per core. Each scheduler owns a dedicated *threadpool* that may be accessed by other schedulers for stealing work. Each node runs a message handler, which shares access to the *sparkpool* with the schedulers. Inter-node communication is abstracted into a *communication layer*, that provides startup and shutdown functionality, node IDs, and peer-to-peer message delivery between nodes. The communication layer in the version of HdpH presented in [114] is based on MPI.

2.7 Fault Tolerance Potential for HdpH

HdpH was designed to have *potential* for fault tolerance. The language implementation isolates the heaps of each distributed node, and hence has the potential to tolerate individual node failures. This thesis realises this fault tolerance potential as a reliable

```
1  -- |Sequential Fibonacci micro-benchmark
2  fib :: Int → Integer
3  fib n | n == 0 = 0
4        | n == 1 = 1
5        | otherwise = fib (n-1) + fib (n-2)
6
7  -- |Fibonacci in HdpH
8  hdphFib :: RTSConf → Int → IO Integer
9  hdphFib conf x = fromJust <$> runParIO conf (hdphFibEval x)
10
11 -- |Fibonacci Par computation
12 hdphFibEval :: Int → Par Integer
13 hdphFibEval x
14     | x == 0 = return 0
15     | x == 1 = return 1
16     | otherwise = do
17         v ← new
18         gv ← glob v
19         spark $(mkClosure [| hdphFibRemote (x, gv) |])
20         y ← hdphFibEval (x - 2)
21         clo_x ← get v
22         force $ unClosure clo_x + y
23
24 -- |Function closure
25 hdphFibRemote :: (Int, GIVar (Closure Integer)) → Par ()
26 hdphFibRemote (n, gv) = hdphFibEval (n - 1) »= force »= rput gv ∘ toClosure
```

Listing 2.5: Fibonacci in HdpH

scheduling extension called HdpH-RS.

Symbolic computation is often distinguished from numerical analysis by the observation that symbolic computation deals with exact computations, while numerical analysis deals with approximate quantities [77]. Therefore, trading precision in HdpH-RS is not a possibility, because solutions must be necessarily exact. This chapter has classified numerous dependable system types (Section 2.1) and existing approaches to fault tolerance (Section 2.2.3). Self stabilisation techniques and probabilistic accuracy bounds can, for example, be used with stochastic simulations to trade precision for reliability by simply discarding lost computations or by smoothing information between neighbouring nodes (Section 2.2.4). Due to the necessary precision of symbolic applications, these mechanisms are unsuitable for HdpH-RS.

HdpH-RS uses a TCP-based transport layer. In contrast to FT-TCP (Section 2.3.4), the resilience in HdpH-RS is implemented at a higher level than TCP — TCP is used to detect node failure, but *recovery* is implemented in the HdpH-RS scheduler.

A collection of algorithmic parallel fault tolerance abstractions is built on top of the HdpH-RS primitives `supervisedSpawn` and `supervisedSpawnAt`, influenced by how the

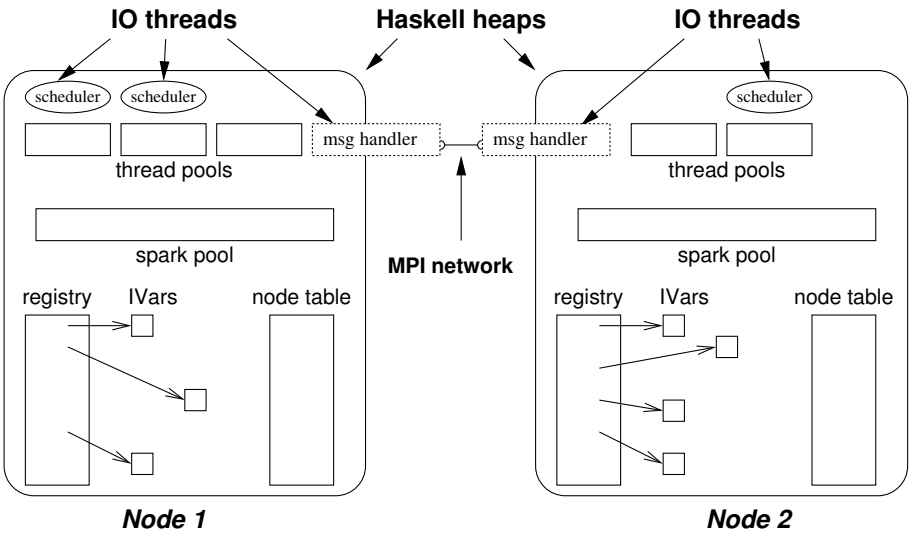


Figure 2.11: HdpH System Architecture

supervision behaviour in Erlang OTP (Section 2.3.7) abstracts over the lower level `link` primitive. The distinction between fault tolerance in CloudHaskell (Section 2.4) and HdpH-RS is how failures are handled. Although CloudHaskell provides the necessary primitives for fault tolerance i.e. process linking and monitoring (Section 2.4.1), parent processes must be programmed to recover from detected failures. In contrast, the HdpH-RS scheduler handles and recovers from faults — the programmer does not need to program with faults in mind.

Chapter 3

Designing a Fault Tolerant Programming Language for Distributed Memory Scheduling

This chapter presents the design of a reliability extension to HdpH, HdpH-RS. The design of HdpH-RS is sensitive to the complexities of asynchronous distributed systems — tracking task migration, detecting failure, and identifying at-risk tasks in the presence of failure. The design forms a foundation for the validation and implementation of a reliable distributed scheduler for HdpH-RS in Chapters 4 and 5. The design of HdpH-RS has three elements:

1. **Fault tolerant programming primitives** The HdpH API is extended with the spawn family of primitives for *fault tolerant* task scheduling, introduced in Section 3.3.2.

2. **A small-step operational semantics** An operational semantics for a simplified definition for the HdpH-RS primitives is given in Section 3.4. It describes the small-step reduction semantics on states for each primitive. Executions through these small-step transitions is in Section 3.4.4.

3. **A reliable distributed scheduler** The algorithms for reliable scheduling is in Section 3.5.4, and are then illustrated with examples in Section 3.5.5. HdpH-RS is resilient to single node and simultaneous failure (Section 3.5.5), such as network partitioning where multiple nodes become detached from the root node at once. The scheduler detects network connection failures due to failures of nodes, networking hardware or software crashes. Failures are encapsulated with isolated heaps for each node, so the loss of one node does not damage other nodes in the architecture.

Why is such a rigorous design processes needed? Would not a carefully constructed reliable scheduler suffice, with human intuition as the verification step in its design? Asynchronous message passing in distributed systems make it extremely difficult maintain a correct understanding of task location, occurrence of task evaluation, and node failure. The work stealing system architecture of HdpH complicates matters further — when tasks are created they can migrate between nodes before they are either evaluated or lost in the presence of failure. Marrying a verified scheduler model and a formalised operational semantics as a design process adds confidence that the HdpH-RS scheduler will evaluate tasks correctly and be resilient to failure.

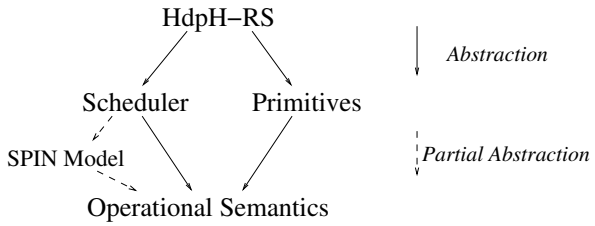


Figure 3.1: Abstraction of Design, Validation & Implementation of HdpH-RS

The relationship between the HdpH-RS primitives and scheduler design (Section 3.3.2), reliable scheduling properties verified with model checking (Chapter 4), the operational semantics (Section 3.4) and Haskell realisation (Chapter 5) are depicted in Figure 3.1. The implementation honours the Promela model verified by SPIN, and the small-step operational semantics. Therefore, the scheduling algorithms in Section 3.5.4, the Promela model in Chapter 4, and implementation in Chapter 5 are frequently cross-referenced to show a consistency from design, through validation, to implementation.

3.1 Supervised Workpools Prototype

A supervised workpools prototype is a strong influence on the HdpH-RS fault tolerant programming primitives and reliable scheduling design. The design and implementation has been published [164], and is described in detail in Appendix A.1. The concept of exposing the fault tolerant programming primitives `supervisedSpawn` and `supervisedSpawnAt` is influenced by the `supervisedWorkpoolEval` primitive. All three allow the user to opt-in to reliable scheduling of tasks. The workpool hides task scheduling, failure detection and task replication from the programmer. Moreover, workpools can be nested to form fault-tolerant hierarchies, which is essential for scaling up to massively parallel platforms.

On top of the supervised workpool, two algorithmic skeletons were produced, encapsu-

lating parallel-map and divide-and-conquer patterns. The technique of abstracting fault tolerant parallel patterns in this way has been elaborated in HdpH-RS, which exposes 10 fault tolerant algorithmic skeletons (Section 6.1.2). The supervised workpool achieved fault tolerance using three techniques — keeping track of where tasks are sent, detecting failure, and replicating tasks that may be lost because of failure. These techniques are extended in the HdpH-RS implementation.

The main limitation of the supervised workpool prototype is its scheduling capability. Tasks are scheduled eagerly and preemptively. There is no opportunity for load balancing between overloaded and idle nodes. The challenge of fault tolerance is greatly increased when a distributed scheduler is required to supervise tasks that can migrate to idle nodes. The HdpH-RS design and implementation is a refined elaboration of the supervised workpools prototype. It supports work stealing, spark location tracking, failure detection, and spark and thread replication. The HdpH-RS implementation feature set matches the HdpH language and scheduler, with the exception of fish hopping (Section 3.5.2). Failure-free runtime overheads are comparative to HdpH, even when scaling to 1400 cores (Section 6.4.2).

3.2 Introducing Work Stealing Scheduling

To minimise application completion times, load-balancing algorithms try to keep all nodes busy performing application related work. If work is not equally distributed between nodes, then some nodes may be idle while others may hold more work than they can immediately execute, wasting the potential performance that a parallel environment offers. The efficiency gained with load balancing are set against communication costs. The distribution of tasks causes communication among the nodes in addition to task execution [176]. Minimising both the idle time and communication overhead are conflicting goals, so load-balancing algorithms have to carefully balance communication-related overhead and processor idle time [152].

Parallel symbolic computation is a good example where load balancing is needed. Symbolic computations often exhibit irregular parallelism, which in turn leads to less common patterns of parallel behaviour [77]. These applications pose significant challenges to achieving scalable performance on large-scale multicore clusters, often require ongoing dynamic load balancing in order to maintain efficiency [54].

Load balancing algorithms have been designed for single site clusters e.g. [189] and wide area networks e.g. [177]. There are many design possibilities for load balancing in wide area networks to consider. These include cluster-aware hierarchical stealing and

cluster-aware load balanced stealing [176]. For single-site clusters, two common load balancing methods are work *pushing* initiated by an overloaded node, and work *stealing* initiated by an idle node.

With random work *pushing*, a node checks after creating or receiving a task whether the task queue length exceeds a certain threshold value. If this is the case, a task from the queue's tail is pushed to a randomly chosen node. This approach aims at minimising node idle time because tasks are pushed ahead of time, before they are actually needed. Random work *stealing* attempts to steal a job from a randomly selected node when a node finds its own work queue empty, repeating steal attempts until it succeeds. This approach minimises communication overhead at the expense of idle time. No communication is performed until a node becomes idle, but then it has to wait for a new task to arrive. When the system load is high, no communication is needed, causing the system to behave well under high loads [176].

The HdpH-RS language supports both work *pushing* and work *stealing*, thanks to the inherited design and implementation of the HdpH scheduler (Section 2.6). The language supports implicit task placement with `spawn`, and explicit placement with `spawnAt`, described in Section 3.3.2. *Sparkpools* hold sparks (closured expressions) that can migrate between nodes in the HdpH architecture. When a node becomes idle, the scheduler looks for work. If the local sparkpool is empty, it will fish for work from remote nodes. If the local sparkpool holds a spark, it is unpacked and added to a local *threadpool* to be evaluated. In this form, threads cannot migrate (again) to other nodes.

This chapter adopts a common terminology for work stealing schedulers [20]. In work stealing strategies, nodes assume dynamically inherited scheduling roles during runtime. *Thieves* are idle nodes with few tasks to compute, or no tasks at all. They steal from *victims* that host more work than they can immediately execute. A thief will randomly select a victim, avoiding deterministic work stealing loops between only a subset of nodes. *Fishing* is the act of a thief attempting to steal work from a chosen victim. The HdpH-RS terminology is described in Section 3.3.1, for now a *spark* can be regarded as a computation that can migrate between nodes. Two examples of the HdpH fishing protocol are shown in Figure 3.2. Thieving node C attempts to steal a spark from victim node B with a fish message, and is successful. Thieving node D is unsuccessful in its fishing message to victim node B.

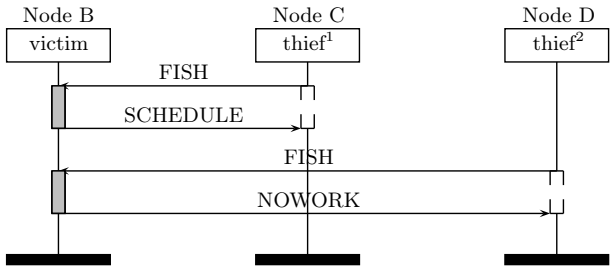


Figure 3.2: Two HdpH Work Stealing Scenarios

3.3 Reliable Scheduling for Fault Tolerance

The fault tolerance is realised in HdpH-RS with two new programming primitives, and a resilient scheduler.

Fault tolerance API The HdpH-RS API provides four new primitives. They provide implicit and explicit parallelism. They are `spawn` and `spawnAt`, and two fault tolerant primitives `supervisedSpawn` and `supervisedSpawnAt`. The definition of a spawned computation defines a close pairing between tasks and values, described in Section 3.3.2.

Reliable scheduler To support the two fault tolerance primitives, the HdpH-RS scheduler includes 7 additional RTS messages, compared to the HdpH scheduler. The recovery of supervised tasks is described algorithmically in Section 3.5.4, and the operational semantics for recovery is given in Section 3.4. The additional runtime system (RTS) messages in the reliable scheduler are described in Section 3.5.1.

The language design provides opt-in reliability. The original plan for the HdpH-RS API was to use the existing HdpH scheduling API, and adding a scheduler flag to indicate that fault tolerant work stealing should be used. An operational semantics (Section 3.4) was attempted for the fault tolerant versions of the HdpH task creation primitives `spark` and `pushTo`. The semantics were complicated by a lack of enforced coupling between tasks and values (`IVar`s). A simpler set of task creation primitives, the spawn family, were designed as a result. The spawn family of primitives (Section 3.3.2) enforce a one-to-one relationship between task expressions and `IVar`s.

3.3.1 HdpH-RS Terminology

Table 3.1 defines a consistent terminology to describe tasks, values, and nodes. The terminology is tied closely to the spawn family of primitives, introduced in Section 3.3.2.

Term	Description
Tasks and values	
Future	A variable that initially holds no value. It will later be filled by evaluating a task expression.
Task Expression	A pure Haskell expression that is packed in to a spark or thread.
Spark	A lazily scheduled task expression to be evaluated and its value written to its corresponding future.
Thread	An eagerly scheduled task expression to be evaluated and its value written to its corresponding future.
Supervision of futures and sparks	
Supervised Future	Same as a future, with an additional guarantee of being eventually filled by its associated task expression even in the presence of remote node failure.
Supervised Spark	A lazily scheduled spark that has its location monitored. A replica of this supervised spark will be re-scheduled by its creator (supervisor) when a previous copy is lost in the presence of failure.
Node roles for work stealing	
Thief	Node that attempts to steal a spark or supervised spark from a chosen victim.
Victim	Node that holds a spark or supervised spark and has been targeted by a thief.
Supervisor	Creator of a supervised future & corresponding supervised spark or thread.
Task Location Tracker	State on a supervisor that knows the location of supervised sparks or threads corresponding to supervised futures that it hosts.

Table 3.1: HdpH-RS Terminology

3.3.2 HdpH-RS Programming Primitives

Listing 3.1 shows the HdpH-RS API. The fault tolerance primitives `supervisedSpawn` and `supervisedSpawnAt` in HdpH-RS on lines 3 and 7 share the same API as their non-fault tolerant counterparts `spawn` and `spawnAt`. This minimises the pain of opting in to (and out of) fault tolerant scheduling. All four of these primitives take an expression as an argument, and return a *future* [95]. A future can be thought of as placeholder for a value that is set to contain a real value once that value becomes known, by evaluating the expression. Futures are implemented with HdpH-RS using a modified version of `IVar`s from HdpH, described in Section 5.1.1. In HdpH-RS, the creation of `IVar`s and the writing of values to `IVar`s is hidden from the programmer, which is instead performed by the spawn primitives. A visualisation of dataflow graph construction using `spawn` and `spawnAt` is shown in Figure 3.3. It is an distributed-memory extension of the dataflow graph scheduling for single nodes presented in the monad-par paper [118].

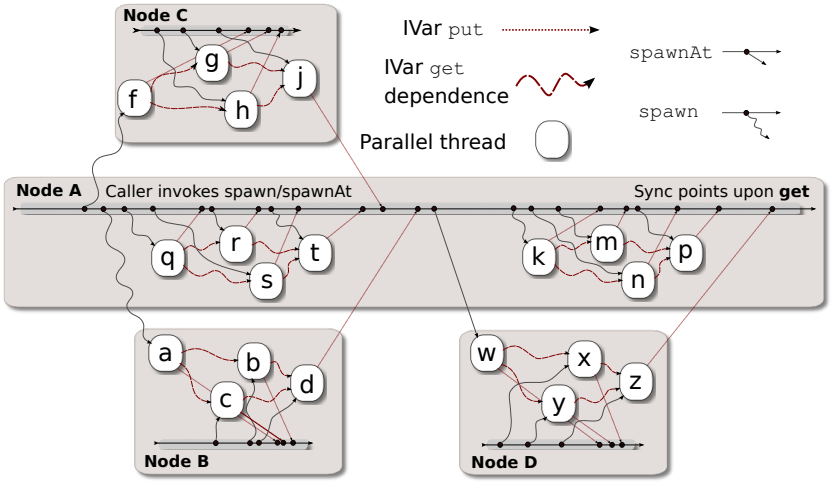


Figure 3.3: Dataflow Parallelism with `spawn`,`spawnAt` and `get`

The following list defines four HdpH-RS primitives at a high level. The naming convention for operations on `IVar` futures in HdpH-RS, namely `spawn` and `get`, is inspired by the monad-par library [118].

`spawn` Takes a closured expression to be filled with the value of the evaluated spark. `IVar` operations `new` and `rput` are hidden from the programmer. It returns an empty `IVar`, and schedules the spark.

`supervisedSpawn` Same as `spawn`, but in this case it invokes the reliable scheduler, which guarantees the execution of the supervised spark.

`spawnAt` Takes a closured expression, and a `NodeId` parameter specifying which node

```
1  -- * Lazy work placement
2  spawn             :: Closure (Par (Closure a)) → Par (IVar (Closure a))
3  supervisedSpawn   :: Closure (Par (Closure a)) → Par (IVar (Closure a))
4
5  -- * Eager work placement
6  spawnAt           :: Closure (Par (Closure a)) → NodeId → Par (IVar (Closure a))
7  supervisedSpawnAt :: Closure (Par (Closure a)) → NodeId → Par (IVar (Closure a))
8
9  -- * IVar operations
10 get    :: IVar a → Par a
11 tryGet :: IVar a → Par (Maybe a)
12 probe  :: IVar a → Par Bool
```

Listing 3.1: HdpH-RS Primitives.

that will be eagerly allocated the thread. Again, the `IVar` operations `new` and `rput` are hidden from the programmer.

`superviseSpawnAt` Same as `spawnAt`, but in this case it invokes the reliable scheduler, which guarantees the execution of the supervised thread. For fault tolerance, the task tracking of the supervised thread is simpler than `supervisedSpawn`. Once the task has been transmitted, the scheduler knows that if the target node dies *and* the `IVar` is empty, then the supervised thread needs recovering.

Regrettably, naming conventions across programming libraries that support futures do not share a common naming convention of primitives for creating and reading futures, and task scheduling. This is explored in greater detail in Appendix A.2, which compares the use of functional futures in the APIs for monad-par [118], Erlang RPC [30], the CloudHaskell Platform [181] and HdpH-RS.

3.4 Operational Semantics

This section gives a small-step operational semantics [129] of the key HdpH-RS primitives outlined in Section 3.3.2. The operational semantics is a small-step reduction semantics on states. It also introduces a number of internal scheduling transitions in HdpH-RS that are used for migrating sparks and writing values to `IVar`s, and recovering lost sparks and threads in the presence of failure.

An operational semantics specifies the behaviour of a programming language by defining a simple abstract machine for it. There are other approaches to formalising language semantics, though the treatment of non-determinism and concurrency in more abstract denotational semantics make them unsuitable in this context [128].

$$
\begin{array}{lll}
\textit{Variables} & x & \text{general variable} \\
\textit{Terms} & L, M, N ::= & x \mid \lambda x.L \mid M\,N \mid \mathbf{fix}\,M \\
\textit{WHNF values} & V ::= & \lambda x.L \mid x\,\bar{L}
\end{array}
$$

$$
[\text{whnf}]\ \frac{}{V \Downarrow V} \qquad [\text{fix}]\ \frac{M\,(\mathbf{fix}\,M) \Downarrow V}{\mathbf{fix}\,M \Downarrow V}
$$

$$
[\text{beta}]\ \frac{M \Downarrow \lambda x.L \qquad L[x := N] \Downarrow V}{M\,N \Downarrow V} \qquad [\text{head}]\ \frac{M \Downarrow x\,\bar{L}}{M\,N \Downarrow x\,\bar{L}\,N}
$$

Figure 3.4: Syntax and Big-Step Semantics of Host Language.

Section 3.4.1 outlines the semantics of the host language, Haskell. Section 3.4.2 describes a simplified HdpH-RS syntax, and Section 3.4.3 defines the operational semantics of these primitives. Section 3.4.4 simulates the execution of transition rules over the global state to demonstrate the execution and recovery of sparks and threads.

3.4.1 Semantics of the Host Language

Being an embedded DSL, the operational semantics of HdpH-RS builds on the semantics of the host language, Haskell. For the sake of presenting a semantics, the host language is assumed to be a standard call-by-name lambda calculus with a fixed-point combinator and some basic data types, like booleans, integers, pairs, and lists.

Figure 3.4 presents syntax and operational semantics for this host language. Note that data types (constructors, projections and case analysis) have been omitted for brevity.

The syntax of terms is standard, including the usual convention that applications associate to the left, and the scopes of lambda abstractions extend as far as possible to the right. The notation $\bar{L}$ is a shorthand for a sequence of applications $L_1\,L_2 \ldots L_n$, for some $n \geq 0$. We write $L[x := N]$ for the term that arises from L by (capture-avoiding) substitution of all free occurrences of x with N.

The big-step operational semantics is also standard for a call-by-name lambda calculus. By induction on derivations, it can be shown that the big-step reduction relation $\Downarrow$ is a partial function the results of which are values in weak head normal form [1].

3.4.2 HdpH-RS Core Syntax

Listing 3.2 shows the core primitives of HdpH-RS. For the purpose of simplifying the semantics, the language presented in Listing 3.2 deviates from the HdpH-RS API (Listing 3.1) in a number of ways. It ignores the issues with closure serialisation. So, there is no

`Closure` type constructor and instead all expressions are assumed serialisable. The syntax does not allow to the programmer to *fork* threads. Although this could be easily added, the focus is on scheduling and recovering remote tasks with the `spawn` family. Read access (`get`) is still restricted to locally hosted `IVar`s. The pure `at` operation is lifted into the `Par` monad. The `rput` operation is not part of the HdpH-RS API, but is an operation in the semantics, hence its inclusion. Pure operations would complicate the semantics needlessly, hence why `at` is monadic. Lastly, the definition of `eval` does not allow `IO` actions to be lifted to `Par` computations, so only pure computations can be lifted.

```
1  -- * Types
2  data Par a    -- Par monad
3  data NodeId   -- explicit locations (shared-memory nodes)
4  data IVar a   -- remotely writable, locally readable one-shot buffers
5
6  -- * IVar operations
7  at    :: IVar a → Par Node    -- query host
8  probe :: IVar a → Par Bool    -- non-blocking local test
9  get   :: IVar a → Par a       -- blocking local read
10 rput  :: IVar a → a → Par () -- put value to IVar (hidden primitive)
11
12 -- * Task scheduling
13 -- spawn
14 spawn             :: Par a  → Par (IVar a)
15 supervisedSpawn   :: Par a  → Par (IVar a)
16
17 -- spawnAt
18 spawnAt           :: NodeId → Par a → Par (IVar a)
19 supervisedSpawnAt :: NodeId → Par a → Par (IVar a)
20
21 -- * Task evaluation
22 eval :: a → Par a  -- evaluate argument to WHNF
```

Listing 3.2: Simplified HdpH-RS Primitives

3.4.3 Small Step Operational Semantics

This section describes small-step operational semantics of HdpH-RS. They extend the HdpH semantics [109] with a set of new states for futures and faults, and transition rules for the spawn family of primitives & spark and thread recovery.

Semantics of HdpH-RS

Figure 3.5 presents the syntax of the HdpH-RS DSL for the purpose of this semantics. They are an extension of the HdpH semantics, with the spawn family of primitives added, and `spark`, `pushTo` and `new` removed. For simplicity, types are elided. However, all terms

$$
\begin{array}{lll}
\textit{Par monad terms} & P, Q ::= & P \gg\!= \lambda x.Q \mid \texttt{return}\, M \mid \texttt{eval}\, M \\
& & \mid \texttt{spawn}\, P \mid \texttt{spawnAt}\, M\, P \\
& & \mid \texttt{supervisedSpawn}\, P \mid \texttt{supervisedSpawnAt}\, M\, P \\
& & \mid \texttt{at}\, M \mid \texttt{probe}\, M \mid \texttt{get}\, M \mid \texttt{rput}\, M\, P \\
\textit{Evaluation contexts} & \mathcal{E} ::= & [\cdot] \mid \mathcal{E} \gg\!= M
\end{array}
$$

Figure 3.5: Syntactic categories required for HdpH-RS small-step semantics.

are assumed well-typed according to the type signatures given in Listing 3.2. Figure 3.5 also introduces evaluation contexts [64] as Par monad terms with a hole, which may be followed by a continuation. Put differently, an evaluation context is a Par monad term, possibly to the left of a bind.

The HdpH-RS semantics is influenced by the monad-par semantics [118], which in turn takes its presentation from the papers on concurrency and asynchronous exceptions in Haskell [94]. A vertical bar | is used to join threads, sparks and `IVar`s into a program state. For example, $i\langle\mathcal{E}[\texttt{get}\, M]\rangle_n \mid j\{N\}_n$ is a program state with a thread labelled i whose next `Par` action is `get`, joined with a full `IVar` labelled j (Table 3.2). The following rule is used for getting values from full `IVar`s, shown later in Figure 3.7.

$$
[\text{get}_i]\ \frac{M \Downarrow j}{i\langle\mathcal{E}[\texttt{get}\, M]\rangle_n \mid j\{N\}_n \mid S \ \rightarrow\ i\langle\mathcal{E}[\texttt{return}\, N]\rangle_n \mid j\{N\}_n \mid S}
$$

This rule says that if the next `Par` action in thread i is `get M` where M is reduced to label j, and this thread is parallel with an `IVar` named j containing N, then the action `get M` can be replaced by `return N`.

States

The operational semantics of HdpH-RS is a small-step reduction semantics on states. A *state* S is a finite partial map from an infinite set of *labels* $\mathcal{N}$ to threads, sparks, and `IVar`s. We denote the finite set of labels defined on S by $\mathit{labels}(S)$, and the empty state (i.e. the state defining no labels) by $\emptyset$. Two states S_1 and S_2 can be composed into a new state $S_1 \mid S_2$, provided that they do not overlap, i.e. $\mathit{labels}(S_1) \cap \mathit{labels}(S_2) = \emptyset$. Thus, states with composition | and identity $\emptyset$ form a commutative partial monoid, that is | is an associative and commutative operation, and $\emptyset$ is neutral with respect to |.

Short hand $i\{?\}_n$ is used to denote an IVar that is either empty or full. Transition rules that use this IVar state do not need to know whether or not the IVar has been

Threads	$i\langle M\rangle_n$ maps label i to a *thread* computing M on node n.
Sparks	$i\langle\langle M\rangle\rangle_n$ maps label i to a *spark* to compute M, currently on node n.
Empty IVars	$i\{\}_n$ maps label i to an *empty IVar* on node n.
Full IVars	$i\{M\}_n$ maps label i to a *full IVar* on node n, filled with M.

Table 3.2: HdpH Atomic States

Supervised spark	$i\langle\langle M\rangle\rangle^{\mathtt{S}}_n$ maps label i to a supervised spark on node n.
Supervised futures	$i\{j\langle\langle M\rangle\rangle^{\mathtt{S}}_{n'}\}_n$ maps label i to an empty IVar on node n, to be filled by the result of the supervised spark j .
Threaded futures	$i\{j\langle M\rangle_{n'}\}_n$ maps label i to an empty IVar on nodes n, to be filled by the result of the supervised thread j .
Faults	$i : dead_n$ maps label i to a notification that node n has died.

Table 3.3: HdpH-RS Atomic States

written to. The notation $|x, y, z| = 3$ denotes three pairwise distinct elements x, y and z. Ultimately, a state is either the special state **Error** or is constructed by composition from *atomic states*. It consists of four types of atomic states inherited from HdpH in Table 3.2, and 4 types of new atomic states for HdpH-RS in Table 3.3.

Transitions

The small-step transition rules embodying HdpH-RS scheduling policy are presented in three parts. First, explicit rules are presented for four primitives in the spawn family and `IVar` operations. Next, the migration and conversion of sparks and supervised sparks are presented. Lastly, the transition rules for killing nodes, and recovering sparks and threads are presented. The transition rules are summarised in Table 3.4, which also identifies the new rules for HdpH-RS i.e. are extensions of HdpH.

Explicit HdpH-RS Primitive Rules The semantics for the spawn family of HdpH-RS primitives are shown in Figure 3.6. The first rule `spawn` takes a task `N`, and two new atomic states are added to the state `S`. The first is an empty `IVar` $j\{\}_n$ and the second $k\langle\langle N \gg\!= \texttt{rput}\ j\rangle\rangle_n$ is a spark that, when converted to a thread, will evaluate `N` to normal form, and write the value to j. The empty `IVar` j is returned immediately, so `spawn` is non-blocking. `IVar` j will always reside on n, and spark k will initially reside on n.

The `supervisedSpawn` rule is identical but with one important distinction, the `IVar` j and spark k are more tightly coupled in $j\{k\langle\langle N \gg\!= \texttt{rput}\ j\rangle\rangle^{\mathtt{S}}_n\}_n$, stating that j will be filled by `rput` the value of evaluating `N` to normal form in k. The `spawnAt` rule shows that the primitive takes two arguments, `M` and `N`. Reducing `M` to weak head normal form is n'

Transition Rules	HdpH-RS Extension
Primitives & Evaluation Contexts, Figure 3.6.	
spawn	✔
supervisedSpawn	✔
spawnAt	✔
supervisedSpawnAt	✔
eval	
bind	
normalize	
IVar Operations, Figure 3.7.	
rput_empty	
rput_empty_supervised_threaded_future	✔
rput_empty_supervised_sparked_future	✔
rput_full	
get	
get_error	
probe_empty	
probe_empty_supervised_threaded_future	✔
probe_empty_supervised_sparked_future	✔
probe_full	
probe_error	
Spark Scheduling, Figure 3.8.	
migrate_spark	
migrate_supervised_spark	✔
convert_spark	
convert_supervised_spark	✔
Failure & Recovery, Figure 3.9.	
kill_node	✔
kill_spark	✔
kill_supervised_spark	✔
kill_thread	✔
kill_ivar	✔
recover_supervised_spark	✔
recover_supervised_thread	✔

Table 3.4: Summary of Transition Rules

$$[\text{spawn}_i]\ \frac{j \notin \mathit{labels}(S) \qquad k \notin \mathit{labels}(S) \qquad |\{i,j,k\}| = 3}{i\langle \mathcal{E}[\mathtt{spawn}\, N]\rangle_n \mid S \ \rightarrow\ i\langle \mathcal{E}[\mathtt{return}\, j]\rangle_n \mid j\{\}_n \mid k\langle\!\langle N \gg\!= \mathtt{rput}\, j\rangle\!\rangle_n \mid S}$$

$$[\text{supervisedSpawn}_i]$$
$$\frac{j \notin \mathit{labels}(S) \qquad k \notin \mathit{labels}(S) \qquad |\{i,j,k\}| = 3}{i\langle \mathcal{E}[\mathtt{supervisedSpawn}\, N]\rangle_n \mid S \ \rightarrow\ i\langle \mathcal{E}[\mathtt{return}\, j]\rangle_n \mid j\{k\langle\!\langle N \gg\!= \mathtt{rput}\, j\rangle\!\rangle^{\mathrm{S}}_n\}_n \mid k\langle\!\langle N \gg\!= \mathtt{rput}\, j\rangle\!\rangle^{\mathrm{S}}_n \mid S}$$

$$[\text{spawnAt}_i]\ \frac{M \Downarrow n' \qquad j \notin \mathit{labels}(S) \qquad k \notin \mathit{labels}(S) \qquad |\{i,j,k\}| = 3}{i\langle \mathcal{E}[\mathtt{spawnAt}\, M\, N]\rangle_n \mid S \ \rightarrow\ i\langle \mathcal{E}[\mathtt{return}\, j]\rangle_n \mid j\{\}_n \mid k\langle N \gg\!= \mathtt{rput}\, j\rangle_{n'} \mid S}$$

$$[\text{supervisedSpawnAt}_i]$$
$$\frac{M \Downarrow n' \qquad j \notin \mathit{labels}(S) \qquad k \notin \mathit{labels}(S) \qquad |\{i,j,k\}| = 3}{i\langle \mathcal{E}[\mathtt{supervisedSpawnAt}\, M\, N]\rangle_n \mid S \ \rightarrow\ i\langle \mathcal{E}[\mathtt{return}\, j]\rangle_n \mid j\{k\langle N \gg\!= \mathtt{rput}\, j\rangle_{n'}\}_n \mid k\langle N \gg\!= \mathtt{rput}\, j\rangle_{n'} \mid S}$$

$$[\text{eval}_i]\ \frac{M \Downarrow V}{i\langle \mathcal{E}[\mathtt{eval}\, M]\rangle_n \mid S \ \rightarrow\ i\langle \mathcal{E}[\mathtt{return}\, V]\rangle_n \mid S}$$

$$[\text{bind}_i]\ \ i\langle \mathcal{E}[\mathtt{return}\, N \gg\!= M]\rangle_n \mid S \ \rightarrow\ i\langle \mathcal{E}[M\, N]\rangle_n \mid S$$

$$[\text{normalize}_i]\ \frac{M \Downarrow V \qquad M \not\equiv V}{i\langle \mathcal{E}[M]\rangle_n \mid S \ \rightarrow\ i\langle \mathcal{E}[V]\rangle_n \mid S}$$

Figure 3.6: Small-step transition rules embodying HdpH-RS Primitives & Evaluation Contexts.

indicating the node to which the expression N `>>=rput` j will be sent. Once again `spawnAt` is non-blocking, and an empty `IVar` j is returned immediately. The `supervisedSpawnAt` couples the supervised future j and supervised thread k, enforcing that the value of `N` reduced to normal form will be written to `IVar` j with `rput`.

Explicit HdpH-RS Transitions on Futures The transitions on futures are in Figure 3.7. The `get` rule takes an argument `M`, which is reduced to `IVar` j that holds the value `M`. This is a blocking operation, and does not return until j has been filled with a value. When value `N` is written to the `IVar`, it is returned to the `get` function caller. For completeness, a rule `get_error` is included. This rule states that if the `IVar` resides on a different node to the `get` function caller, then the program will exit with an **Error**. This is because the model of HdpH-RS is that `IVar`s always stay on the node that created them, and reading a `IVar` remotely violates the model.

One difference between HdpH and HdpH-RS is that `rput` is hidden in the HdpH-RS API. Nevertheless, it is used internally by the four spawn rules, hence its inclusion in the HdpH-RS transition rules. It takes two arguments M and N. M reduces to a `IVar` label j. N is the value to be written to the `IVar`. In the `rput_empty` rule, the future is filled with N in thread i. In the `rput_supervised_empty` rule, the supervised future j is either to be filled with N, the value of executing supervised spark $k\langle\!\langle V \rangle\!\rangle^{\mathrm{S}}_{n'}$ or thread $k\langle V \rangle_{n'}$. The *post*-state is a full future holding N.

The rule `rput_full` is triggered when an `rput` attempt is made to a `IVar` that already holds a value. The rule shows how this write attempt is silently ignored, an important property for fault tolerance. Section 3.5.3 explains how identical computations may be raced against one another, with the first write attempt to the `IVar` succeeding. The write semantics in monad-par is different. If a second write attempt is made to an `IVar` in monad-par, the program exits with an error because monad-par insists on determinism.

The `probe` primitive is used by the scheduler to establish which `IVar`s are empty at the point of node failure i.e. identifying the sparks and threads that need replicating. In `probe_empty`, `probe` takes an argument `M` reduced to j, an `IVar` label. If j is empty i.e. $j\{\}_n$, $j\{k\langle V \rangle_{n'}\}_n$ or $j\{k\langle\!\langle V \rangle\!\rangle^{\mathrm{S}}_{n'}\}_n$, then `False` is returned. The `probe_full` rule is triggered when the `IVar` $j\{N\}_n$ is full, and `True` is returned. As with `get_error`, if a node attempts to probe a `IVar` that is does not host, an **Error** is thrown.

Spark Migration & Conversion The spark migration and conversion transition rules are shown in Figure 3.8. The `migrate_spark` transition moves a supervised spark $j\langle\!\langle N \rangle\!\rangle_n$ from node n to n'. The `migrate_supervised_spark` transition modifies two states. First, the supervised spark $j\langle\!\langle N \rangle\!\rangle^{\mathrm{S}}_n$ migrates to node n''. Second, the state of its corresponding

$$[\text{rput\_empty}_i]\ \frac{M \Downarrow j}{i\langle \mathcal{E}[\texttt{rput}\ M\ N]\rangle_{n'} \mid j\{\}_n \mid S \ \rightarrow\ i\langle \mathcal{E}[\texttt{return ()}]\rangle_{n'} \mid j\{N\}_n \mid S}$$

$$[\text{rput\_empty\_supervised\_threaded\_future}_i]\ \frac{M \Downarrow j}{i\langle \mathcal{E}[\texttt{rput}\ M\ N]\rangle_{n'} \mid j\{k\langle M\rangle_{n''}\}_n \mid S \ \rightarrow\ i\langle \mathcal{E}[\texttt{return ()}]\rangle_{n'} \mid j\{N\}_n \mid S}$$

$$[\text{rput\_empty\_supervised\_sparked\_future}_i]\ \frac{M \Downarrow j}{i\langle \mathcal{E}[\texttt{rput}\ M\ N]\rangle_{n'} \mid j\{k\langle\!\langle M\rangle\!\rangle^{\mathbb{S}}_{n''}\}_n \mid S \ \rightarrow\ i\langle \mathcal{E}[\texttt{return ()}]\rangle_{n'} \mid j\{N\}_n \mid S}$$

$$[\text{rput\_full}_i]\ \frac{M \Downarrow j}{i\langle \mathcal{E}[\texttt{rput}\ M\ N]\rangle_{n'} \mid j\{N'\}_n \mid S \ \rightarrow\ i\langle \mathcal{E}[\texttt{return ()}]\rangle_{n'} \mid j\{N'\}_n \mid S}$$

$$[\text{get}_i]\ \frac{M \Downarrow j}{i\langle \mathcal{E}[\texttt{get}\ M]\rangle_{n} \mid j\{N\}_n \mid S \ \rightarrow\ i\langle \mathcal{E}[\texttt{return}\ N]\rangle_{n} \mid j\{N\}_n \mid S}$$

$$[\text{get\_error}_i]\ \frac{M \Downarrow j \qquad n' \neq n}{i\langle \mathcal{E}[\texttt{get}\ M]\rangle_{n'} \mid j\{?\}_n \mid S \ \rightarrow\ \textbf{Error}}$$

$$[\text{probe\_empty}_i]\ \frac{M \Downarrow j}{i\langle \mathcal{E}[\texttt{probe}\ M]\rangle_{n} \mid j\{\}_n \mid S \ \rightarrow\ i\langle \mathcal{E}[\texttt{return False}]\rangle_{n} \mid j\{\}_n \mid S}$$

$$[\text{probe\_empty\_supervised\_threaded\_future}_i]\ \frac{M \Downarrow j}{i\langle \mathcal{E}[\texttt{probe}\ M]\rangle_{n} \mid j\{k\langle M\rangle_{n'}\}_n \mid S \ \rightarrow\ i\langle \mathcal{E}[\texttt{return False}]\rangle_{n} \mid j\{k\langle M\rangle_{n'}\}_n \mid S}$$

$$[\text{probe\_empty\_supervised\_sparked\_future}_i]\ \frac{M \Downarrow j}{i\langle \mathcal{E}[\texttt{probe}\ M]\rangle_{n} \mid j\{k\langle\!\langle M\rangle\!\rangle^{\mathbb{S}}_{n'}\}_n \mid S \ \rightarrow\ i\langle \mathcal{E}[\texttt{return False}]\rangle_{n} \mid j\{k\langle\!\langle M\rangle\!\rangle^{\mathbb{S}}_{n'}\}_n \mid S}$$

$$[\text{probe\_full}_i]\ \frac{M \Downarrow j}{i\langle \mathcal{E}[\texttt{probe}\ M]\rangle_{n} \mid j\{N\}_n \mid S \ \rightarrow\ i\langle \mathcal{E}[\texttt{return True}]\rangle_{n} \mid j\{N\}_n \mid S}$$

$$[\text{probe\_error}_i]\ \frac{M \Downarrow j \qquad n' \neq n}{i\langle \mathcal{E}[\texttt{probe}\ M]\rangle_{n'} \mid j\{?\}_n \mid S \ \rightarrow\ \textbf{Error}}$$

Figure 3.7: Small-Step Transition Rules Embodying Future Operations.

$$[\text{migrate\_spark}_j]\ \frac{n' \neq n}{j\langle\!\langle N \rangle\!\rangle_n \mid S \ \rightarrow\ j\langle\!\langle N \rangle\!\rangle_{n'} \mid S}$$

$$[\text{migrate\_supervised\_spark}_j]\ \frac{n \neq n''}{j\langle\!\langle N \rangle\!\rangle^S_n \mid i\{j\langle\!\langle N \rangle\!\rangle^S_n\}_{n'} \mid S \ \rightarrow\ j\langle\!\langle N \rangle\!\rangle^S_{n''} \mid i\{j\langle\!\langle N \rangle\!\rangle^S_{n''}\}_n \mid S}$$

$$[\text{convert\_spark}_j]\ \frac{}{j\langle\!\langle M \rangle\!\rangle_n \mid S \ \rightarrow\ j\langle M \rangle_n \mid S}$$

$$[\text{convert\_supervised\_spark}_j]\ \frac{}{j\langle\!\langle M \rangle\!\rangle^S_n \mid S \ \rightarrow\ j\langle M \rangle_n \mid S}$$

Figure 3.8: Small-Step Transition Rules For Spark Migration & Conversion.

supervised future i on node n' is modified to reflect this migration. Constraining the migration of obsolete supervised spark replicas is in rule `migrate_supervised_spark`. The j label on the left hand side of the rule ensures that only the youngest replica of a spark can migrate. The `convert_spark` rule shows that the spark j is converted to a thread.

Fault Tolerance Rules The rules for killing nodes, losing sparks, threads and `IVar`s, and recovering sparks and threads are shown in Figure 3.9. Nodes can fail at any moment. Thus, there are no conditions for triggering the `kill_node` rule. It adds a new state $i : dead_n$ indicating node n is dead. When a node fails, all state on that node is also removed from state S. The presence of $dead_n$ means that sparks, threads and `IVar`s on n are lost with rules `kill_spark`, `kill_thread` and `kill_ivar`.

The transition rules for fault tolerance in HdpH-RS are `recover_supervised_spark` and `recover_supervised_thread`, shown in Figure 3.9. They are internal transitions, and fault recovery is done by the scheduler, not the programmer. There are two considerations for recovering sparks and threads.

1. The candidate tasks for replication are those whose most recent tracked location was the failed node.

2. Of these tasks, they are rescheduled if not yet evaluated i.e. its corresponding `IVar` is empty.

The `recover_supervised_spark` rule is triggered if node n' has died, and a `IVar` j is empty, shown as $j\{\langle\!\langle N \rangle\!\rangle_{n'}\}_n$. As node n' is dead, `IVar` j will only be filled if the task is rescheduled. The post-state includes a new supervised spark k that will write to j. The spark is allocated initially into the sparkpool on node n, the node that hosts the `IVar`.

$$[\text{kill\_node}_n]\ \frac{}{S \ \rightarrow \ i : dead_n \mid S}$$

$$[\text{kill\_spark}_i]\ \frac{}{i\langle\!\langle M \rangle\!\rangle_n \mid j\ dead_n \mid S \ \rightarrow \ j\ dead_n \mid S}$$

$$[\text{kill\_supervised\_spark}_i]\ \frac{}{i\langle\!\langle M \rangle\!\rangle^S_n \mid j\ dead_n \mid S \ \rightarrow \ j\ dead_n \mid S}$$

$$[\text{kill\_thread}_i]\ \frac{}{i\langle M \rangle_n \mid j : dead_n \mid S \ \rightarrow \ j : dead_n \mid S}$$

$$[\text{kill\_ivar}_i]\ \frac{}{i\{?\}_n \mid j : dead_n \mid S \ \rightarrow \ j : dead_n \mid S}$$

$$[\text{recover\_supervised\_spark}_j]\ \frac{n' \neq n \qquad k \notin labels(S) \qquad |\{i,j,k,p\}| = 4}{p : dead_{n'} \mid i\{j\langle\!\langle N \rangle\!\rangle^S_{n'}\}_n \mid S \ \rightarrow \ p : dead_{n'} \mid i\{k\langle\!\langle N \rangle\!\rangle^S_n\}_n \mid k\langle\!\langle N \rangle\!\rangle^S_n \mid S}$$

$$[\text{recover\_supervised\_thread}_j]\ \frac{n' \neq n \qquad k \notin labels(S) \qquad |\{i,j,k,p\}| = 4}{p : dead_{n'} \mid i\{j\langle N \rangle_{n'}\}_n \mid S \ \rightarrow \ p : dead_{n'} \mid i\{k\langle N \rangle_n\}_n \mid k\langle N \rangle_n \mid S}$$

Figure 3.9: Small-step transition rules embodying HdpH-RS Task Recovery.

The same pre-conditions apply for triggering `recover_thread`. That is, a thread needs re-scheduling if it has been pushed to node n' with `supervisedSpawnAt`, and the corresponding `IVar` j is empty. The post-state is a thread k in the threadpool of node n that also hosts j. This thread cannot migrate to another node.

3.4.4 Execution of Transition Rules

This section uses the transition rules from Section 3.4.3 to execute 4 simple programs. The first shows a sequence of transitions originating from `supervisedSpawn` in the absence of faults. The second shows the execution of `supervisedSpawn` in the presence of a node failure. The third shows the execution of `supervisedSpawnAt` in the presence of a node failure. The fourth shows another execution of `supervisedSpawn` in the presence of failure, and demonstrates the non-deterministic semantics of multiple `rput` attempts.

The execution of $3 + 3$ using `supervisedSpawn` is shown in Figure 3.10. It creates `IVar` with the label 2, and spark with the label 3. The spark migrates to node n', where it is converted to a thread. The $3+3$ expression is evaluated and bound. The `rput_empty` rule then fills the `IVar` 2 with the value 6.

The execution in Figure 3.11 evaluates $2 + 2$ with `supervisedSpawn` and includes a failure. As in Figure 3.10, spark 3 is migrated to node n'. At this point, node n' fails. The `kill_supervised_spark` also removes spark 3, which resided on n' when it failed. The

$\rightarrow 1\langle supervisedSpawn\ (eval\ (3+3))\rangle_n$

[supervisedSpawn$_1$]

$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{3\langle\!\langle eval\ (3+3) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_n\}_n \mid 3\langle\!\langle eval\ (3+3) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_n$

[migrate_supervised_spark$_3$]

$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{3\langle\!\langle eval\ (3+3) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_{n'}\}_n \mid 3\langle\!\langle eval\ (3+3) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_{n'}$

[convert_supervised_spark$_3$]

$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{3\langle\!\langle eval\ (3+3) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_{n'}\}_n \mid 3\langle eval\ (3+3) \gg\!= \texttt{rput}\ 2\rangle_{n'}$

[eval$_3$]

$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{3\langle\!\langle eval\ (3+3) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_{n'}\}_n \mid 3\langle \texttt{return}\ 6 \gg\!= \texttt{rput}\ 2\rangle_{n'}$

[bind$_3$]

$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{3\langle\!\langle eval\ (3+3) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_{n'}\}_n \mid 3\langle \texttt{rput}\ 2\ 6\rangle_{n'}$

[rput_empty_supervised_sparked_future$_3$]

$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{6\}_n \mid 3\langle \texttt{return}\ ()\rangle_{n'}$

Figure 3.10: Migration & Execution of Supervised Spark in Absence of Faults

`recover_supervised_spark` rule is triggered, creating a new spark 5 hosted on node n. Spark 5 migrates to node n''. Here, it is converted to a thread. The expression $2 + 2$ is evaluated to 4. This value is `rput` to future 2, from thread 5 on n''.

The execution in Figure 3.12 evaluates $9 + 2$ with `supervisedSpawnAt` and includes a failure. The `supervisedSpawnAt` rule creates a future 2, and thread 3 on node n'. The $9 + 2$ expression is evaluated. The next transition is `kill_node` in relation to node n'', where the thread resides. The `kill_supervised_thread` rule removes thread 3 from the abstract state machine. The thread is replicated as thread 5 on the same node n as the future. The $9 + 2$ expression is once again evaluated. The future 2 is filled with value 11 from thread 5, also on node n.

The execution in Figure 3.13 demonstrates the non-deterministic semantics of multiple `rput` attempts. This occurs when an intermittently faulty node executes an `rput` call. The node's failure may have been detected, though the sparks and threads it hosts may not necessarily be lost immediately. It presents a scenario where a supervised spark is replicated. An obsolete replica is an old copy of a spark. The semantics guarantee that obsolete replicas cannot be migrated, in the `migrate_supervised_spark` rule. The implementation that ensures obsolete replicas are not migrated is described in Section 5.1.1.

The `supervisedSpawn` primitive is used to create an empty future 2 and spark 3 on node n. Converting and executing the spark will write the value of expression $2 + 2$ to future 2. Spark 3 is migrated to node n'. Next, a failure of node n' is perceived,

$\rightarrow 1\langle \mathit{supervisedSpawn}\ (\mathit{eval}\ (2+2))\rangle_n$
[supervisedSpawn$_1$]
$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{3\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\mathcal{S}}_n\}_n \mid 3\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\mathcal{S}}_n$
[migrate_supervised_spark$_3$]
$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{3\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\mathcal{S}}_{n'}\}_n \mid 3\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\mathcal{S}}_{n'}$
[kill_node$_{n'}$]
$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{3\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\mathcal{S}}_{n'}\}_n \mid 3\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\mathcal{S}}_{n'} \mid 4 : \mathit{dead}_{n'}$
[kill_supervised_spark$_3$]
$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{3\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\mathcal{S}}_{n'}\}_n \mid 4 : \mathit{dead}_{n'}$
[recover_supervised_spark$_3$]
$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{5\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\mathcal{S}}_n\}_n \mid 4 : \mathit{dead}_{n'} \mid 5\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\mathcal{S}}_n$
[migrate_supervised_spark$_5$]
$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{5\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\mathcal{S}}_{n''}\}_n \mid 4 : \mathit{dead}_{n'} \mid 5\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\mathcal{S}}_{n''}$
[convert_supervised_spark$_5$]
$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{5\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\mathcal{S}}_{n''}\}_n \mid 4 : \mathit{dead}_{n'} \mid 5\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle_{n''}$
[eval$_5$]
$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{5\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\mathcal{S}}_{n''}\}_n \mid 4 : \mathit{dead}_{n'} \mid 5\langle \texttt{return}\ 4 \gg\!= \texttt{rput}\ 2\rangle_{n''}$
[bind$_5$]
$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{5\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\mathcal{S}}_{n''}\}_n \mid 4 : \mathit{dead}_{n'} \mid 5\langle \texttt{rput}\ 2\ 4\rangle_{n''}$
[rput_empty_supervised_sparked_future$_5$]
$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{4\}_n \mid 4 : \mathit{dead}_{n'} \mid 5\langle \texttt{return}\ ()\rangle_{n''}$

Figure 3.11: Migration & Execution of Supervised Spark in Presence of a Fault

$\rightarrow 1\langle \mathit{supervisedSpawnAt}\ (\mathit{eval}\ 9+2)\ n' \rangle_n$

[supervisedSpawnAt$_1$]

$\rightarrow 1\langle \texttt{return}\ 2 \rangle_n \mid 2\{3\langle \mathit{eval}\ (9+2) \gg\!= \texttt{rput}\ 2 \rangle_{n'}\}_n \mid 3\langle \mathit{eval}\ (9+2) \gg\!= \texttt{rput}\ 2 \rangle_{n'}$

[eval$_3$]

$\rightarrow 1\langle \texttt{return}\ 2 \rangle_n \mid 2\{3\langle\!\langle \mathit{eval}\ (9+2) \gg\!= \texttt{rput}\ 2 \rangle\!\rangle^{\mathbb{S}}_{n'}\}_n \mid 3\langle \texttt{return}\ 11 \gg\!= \texttt{rput}\ 2 \rangle_{n'}$

[kill_node$_{n'}$]

$\rightarrow 1\langle \texttt{return}\ 2 \rangle_n \mid 2\{3\langle\!\langle \mathit{eval}\ (9+2) \gg\!= \texttt{rput}\ 2 \rangle\!\rangle^{\mathbb{S}}_{n'}\}_n \mid 3\langle \texttt{return}\ 11 \gg\!= \texttt{rput}\ 2 \rangle_{n'} \mid 4 : \mathit{dead}_{n'}$

[kill_supervised_thread$_3$]

$\rightarrow 1\langle \texttt{return}\ 2 \rangle_n \mid 2\{3\langle\!\langle \mathit{eval}\ (9+2) \gg\!= \texttt{rput}\ 2 \rangle\!\rangle^{\mathbb{S}}_{n'}\}_n \mid 4 : \mathit{dead}_{n'}$

[recover_supervised_thread$_3$]

$\rightarrow 1\langle \texttt{return}\ 2 \rangle_n \mid 2\{5\langle \mathit{eval}\ (9+2) \gg\!= \texttt{rput}\ 2 \rangle_n\}_n \mid 4 : \mathit{dead}_{n'} \mid 5\langle \mathit{eval}\ (9+2) \gg\!= \texttt{rput}\ 2 \rangle_n$

[eval$_5$]

$\rightarrow 1\langle \texttt{return}\ 2 \rangle_n \mid 2\{5\langle \mathit{eval}\ (9+2) \gg\!= \texttt{rput}\ 2 \rangle_n\}_n \mid 4 : \mathit{dead}_{n'} \mid 5\langle \texttt{return}\ 11 \gg\!= \texttt{rput}\ 2 \rangle_n$

[bind$_5$]

$\rightarrow 1\langle \texttt{return}\ 2 \rangle_n \mid 2\{5\langle \mathit{eval}\ (9+2) \gg\!= \texttt{rput}\ 2 \rangle_n\}_n \mid 4 : \mathit{dead}_{n'} \mid 5\langle \texttt{rput}\ 2\ 11 \rangle_n$

[rput_empty_supervised_threaded_future$_5$]

$\rightarrow 1\langle \texttt{return}\ 2 \rangle_n \mid 2\{11\}_n \mid 4 : \mathit{dead}_{n'} \mid 5\langle \texttt{return}\ () \rangle_n$

Figure 3.12: Migration & Execution of Supervised Thread in Presence of Fault

triggering the `kill_node` rule. Spark 3 is recovered by replicating it as spark 5, again on node n. The label for the spark inside the future 2 has changed from 3 to 5 by the `recover_supervised_spark` rule. This ensures that the `migrate_supervised_spark` rule can no longer be triggered for the obsolete spark 3 on node n'.

Spark 5 migrates to a 3rd node n''. Here, it is converted to a thread and the $2 + 2$ expression evaluated to 4. Despite the failure detection on node n', it has not yet completely failed. Thus, spark 3 on node n' has not yet been killed with `kill_spark`. It is converted to a thread and the $2 + 2$ expression evaluated to 4. The `rput_empty` rule is triggered for the `rput` call in thread 3 on node n'. The future 2 is now full with the value 4. The `rput` call is then executed in thread 5. This triggers the `rput_full` rule. That is, future 2 is already full, so the `rput` attempt on node n'' is silently ignored on node n. The non-deterministic semantics of `rput_empty` and `rput_full` require the side effect of expressions in sparks and threads to be idempotent [136] i.e. side effects whose repetition cannot be observed. The scenario in Figure 3.13 uses a pure $2 + 2$ expression (i.e. with idempotent side effects) to demonstrate spark recovery.

3.5 Designing a Fault Tolerant Scheduler

3.5.1 Work Stealing Protocol

This section presents the protocol for fault tolerant work stealing. It adds resiliency to the scheduling of sparks and threads. These are non-preemptive tasks that are load balanced between overloaded and idle nodes. Non-preemptive tasks are tasks that cannot be migrated once evaluation has begun, in contrast to a partially evaluated preemptive task that *can* be migrated [152].

The fishing protocol in HdpH involves a victim and a thief. The HdpH-RS *fault tolerant* fishing protocol involves a third node — a *supervisor*. A supervisor is the node where a supervised spark was created. The runtime system messages in HdpH-RS serve two purposes. First, to schedule sparks from heavily loaded nodes to idle nodes. Second, to allow supervisors to track the location of supervised sparks as they migrate between nodes.

The UML Message Sequence Notation (MSC) is used extensively in this section. An MSC LaTeXmacro package [121] has been extended to draw all MSC figures. The fault oblivious fishing protocol in HdpH is shown in Figure 3.14. The fault tolerant fishing protocol in HdpH-RS is shown in Figure 3.15. In this illustration, an idle *thief* node C targets a *victim* node B by sending a `FISH` message. The victim requests a scheduling authorisation from the *supervisor* with `REQ`. The supervisor grants authorisation with

$\rightarrow 1\langle \mathit{supervisedSpawn}\ (\mathit{eval}\ (2+2))\rangle_n$

[supervisedSpawn$_1$]

$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{3\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_n\}_n \mid 3\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_n$

[migrate_supervised_spark$_3$]

$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{3\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_{n'}\}_n \mid 3\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_{n'}$

[kill_node$_{n'}$]

$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{3\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_{n'}\}_n \mid 3\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_{n'} \mid 4 : \mathit{dead}_{n'}$

[recover_supervised_spark$_3$]

$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{5\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_n\}_n \mid 3\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_{n'} \mid 4 : \mathit{dead}_{n'}$
$\quad \mid 5\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_n$

[migrate_supervised_spark$_5$]

$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{5\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_{n''}\}_n \mid 3\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_{n'} \mid 4 : \mathit{dead}_{n'}$
$\quad \mid 5\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_{n''}$

[convert_supervised_spark$_5$]

$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{5\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_{n''}\}_n \mid 3\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_{n'} \mid 4 : \mathit{dead}_{n'}$
$\quad \mid 5\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle_{n''}$

[eval$_5$]

$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{5\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_{n''}\}_n \mid 3\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_{n'} \mid 4 : \mathit{dead}_{n'}$
$\quad \mid 5\langle \texttt{return}\ 4 \gg\!= \texttt{rput}\ 2\rangle_{n''}$

[bind$_5$]

$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{5\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_{n''}\}_n \mid 3\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_{n'} \mid 4 : \mathit{dead}_{n'}$
$\quad \mid 5\langle \texttt{rput}\ 2\ 4\rangle_{n''}$

[convert_supervised_spark$_3$]

$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{5\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_{n''}\}_n \mid 3\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle_{n'} \mid 4 : \mathit{dead}_{n'}$
$\quad \mid 5\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle_{n''}$

[eval$_3$]

$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{5\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_{n''}\}_n \mid 3\langle \texttt{return}\ 4 \gg\!= \texttt{rput}\ 2\rangle_{n'} \mid 4 : \mathit{dead}_{n'}$
$\quad \mid 5\langle \texttt{return}\ 4 \gg\!= \texttt{rput}\ 2\rangle_{n''}$

[bind$_3$]

$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{5\langle\!\langle \mathit{eval}\ (2+2) \gg\!= \texttt{rput}\ 2\rangle\!\rangle^{\S}_{n''}\}_n \mid 3\langle \texttt{rput}\ 2\ 4\rangle_{n'} \mid 4 : \mathit{dead}_{n'}$
$\quad \mid 5\langle \texttt{rput}\ 2\ 4\rangle_{n''}$

[rput_empty_supervised_sparked_future$_3$]

$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{4\}_n \mid 3\langle \texttt{return}\ ()\rangle_{n'} \mid 4 : \mathit{dead}_{n'} \mid 5\langle \texttt{rput}\ 2\ 4\rangle_{n''}$

[rput_full$_5$]

$\rightarrow 1\langle \texttt{return}\ 2\rangle_n \mid 2\{4\}_n \mid 3\langle \texttt{return}\ ()\rangle_{n'} \mid 4 : \mathit{dead}_{n'} \mid 5\langle \texttt{return}\ ()\rangle_{n''}$

Figure 3.13: Duplicating Sparks & `rput` Attempts

AUTH, and a spark is scheduled from the victim to the thief in a SCHEDULE message. When the thief receives this, it sends an ACK to the supervisor.

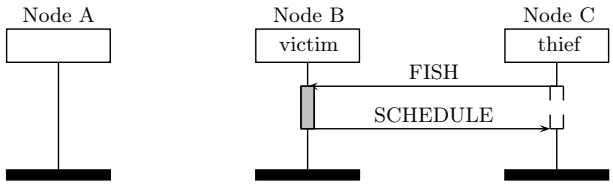


Figure 3.14: Fault Oblivious Fishing Protocol in HdpH

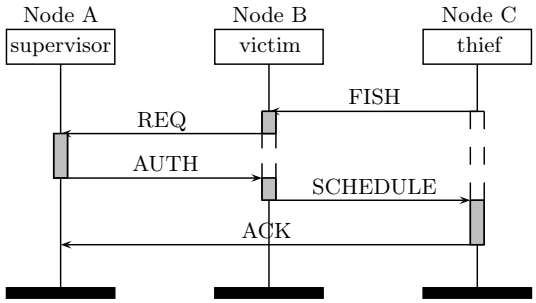


Figure 3.15: Fault Tolerant Fishing Protocol in HdpH-RS

RTS Messages to Support the Work Stealing Protocol

The HdpH-RS RTS messages are described in Table 3.5. The *Message* header is the message type, the *From* and *To* fields distinguish a supervisor node (S) and worker nodes (W), and *Description* shows the purpose of the message. The use of each message are described in the scheduling algorithms in Section 3.5.4.

3.5.2 Task Locality

For the supervisor to determine whether a spark is lost when a remote node has failed, the migration of a supervised spark needs to be tracked. This is made possible from the RTS messages REQ and ACK described in Section 5.5.3.

Task migration tracking is in shown in Figure 3.16. The messages REQ and ACK are received by the supervising node A to keep track of a spark's location. Sparks and threads can therefore be identified by their corresponding globalised IVar. If a spark is created with supervisedSpawn, then the supervised spark's structure is composed of three parts. First, an identifier corresponding the IVar that will be filled by evaluating the task expression in the spark. Second, a replica number of the spark. Third, the task expression inside the spark to be evaluated. In Figure 3.16 the IVar is represented as iX e.g. i2, and

Message	From	To	Description
RTS Messages inherited from HdpH			
`FISH` *thief*	W	W	Fishing request from a thief.
`SCHEDULE` *spark victim*	W	W	Victim schedules a spark to a thief.
`NOWORK`	W	W	Response to `FISH`: victim informs thief that it either does not hold a spark, or was not authorised to schedule a spark.
HdpH-RS RTS Messages for task supervision & fault detection			
`REQ` *ref seq victim thief*	W	S	Victim requests authorisation from supervisor to schedule spark to a thief.
`DENIED` *thief*	S	W	Supervisor denies a scheduling request with respect to `REQ`.
`AUTH` *thief*	S	W	Supervisor authorises a scheduling request with respect to `REQ`.
`OBSOLETE` *thief*	S	W	In response to `REQ`: the task waiting to be scheduled by victim is an obsolete task copy. Victim reacts to `OBSOLETE` by discarding task and sending `NOWORK` to thief.
`ACK` *ref seq thief*	W	S	Thief sends an `ACK` to the supervisor of a spark it has received.
`DEADNODE` *node*	S	S	Transport layer informs supervisor to reschedule sparks that *may* have been lost on failed node.
`DEADNODE` *node*	W	W	Transport layer informs thief to stop waiting for a reply to a `FISH` sent to failed victim.

Table 3.5: HdpH-RS RTS Messages

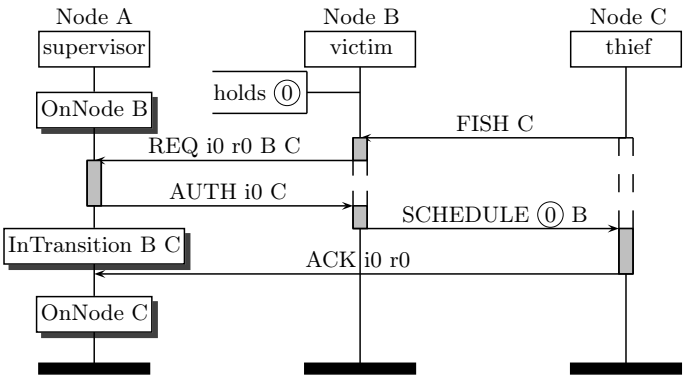


Figure 3.16: Migration Tracking with Message Passing

the replica number as `rX` e.g. `r2`. They are used by the victim node B to request scheduling authorisation, and by thieving node C to acknowledge the arrival of the supervised spark.

The message `REQ` is used to request authorisation to schedule the spark to another node. If the supervisor knows that it is in the sparkpool of a node (i.e. `OnNode thief`) then it will authorise the fishing request with `AUTH`. If the supervisor believes it is in-flight between two nodes (i.e. `InTransition victim thief`) then it will deny the request with `DENIED`. An example of this is shown in Figure 3.17. It is covered by Algorithm 3 later in Section 3.5.4.

A slightly more complex fishing scenario is shown in Figure 3.17. It is covered by Algorithm 2. Node C has sent a fish to node B, prompting an authorisation request to

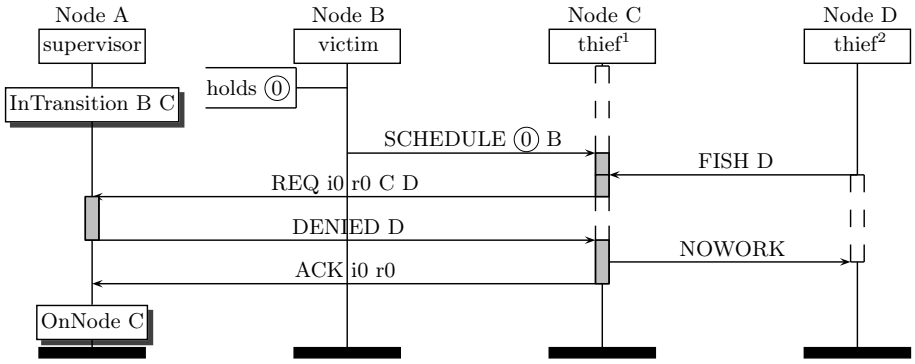


Figure 3.17: Failed Work Stealing Attempt When Spark Migration is Not Yet `ACK`d

the supervisor, node A. During this phase, node D sends a fish to node B. As B is already a victim of node C, the fish is rejected with a `NOWORK` response.

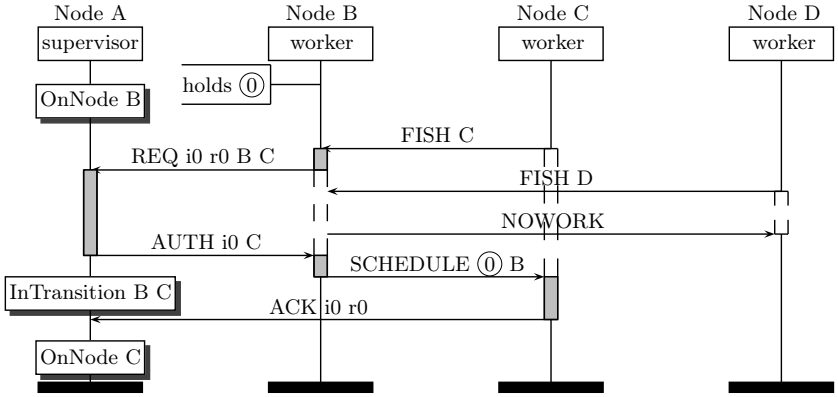


Figure 3.18: Fish Rejected from a Victim of Another Thief

Tracking the Migration of Supervised Tasks

Section 3.5.2 has so far described the migration tracking of one task. In reality, many calls of the spawn family of primitives per node are likely. A reference for a supervised spark or thread is identified by the globalised `IVar` that it will fill.

Table 3.6: Local Registry on Node A When Node B Fails

Function Call on A	IVar Reference	Location	Vulnerable
supervisedSpawnAt $(f\,x)$ B	1	`OnNode B`	$\star$
supervisedSpawn $(h\,x)$	2	`InTransition D C`	
supervisedSpawn $(j\,x)$	3	`InTransition B C`	$\star$
supervisedSpawn $(k\,x)$	4	`OnNode A`	
supervisedSpawnAt $(m\,x)$ D	5	`OnNode D`	

The migration trace for a supervised spark or thread is held within the state of its associated empty `IVar`. A simple local `IVar` registry is shown in Table 3.6, generated be

```
1  -- | Par computation that generates registry entries in Table 3.6
2  foo :: Int → Par Integer
3  foo x = do
4      ivar1 ← supervisedSpawnAt $(mkClosure [| f x |]) nodeB
5      ivar2 ← supervisedSpawn   $(mkClosure [| h x |])
6      ivar2 ← supervisedSpawn   $(mkClosure [| j x |])
7      ivar2 ← supervisedSpawn   $(mkClosure [| k x |])
8      ivar2 ← supervisedSpawnAt $(mkClosure [| m x |]) nodeD
9      x ← get ivar1
10     y ← get ivar2
11     {- omitted -}
```

Listing 3.3: Par Computation That Modifies Local Registry on Node A

executing the code fragment in Listing 3.3 is executed on node A. Five futures (`IVar`s) have been created on node A. Node A expects `REQ` and `ACK` messages about each future it supervises, from victims and thieves respectively. The registry is used to identify which sparks and threads need recovering. Table 3.6 shows which tasks are at-risk when the failure of node B is detected by node A. If node A receives a `DEADNODE B` message from the transport layer, the tasks for `IVar`s 1 and 3 are replicated. The replication of task 3 *may* lead to duplicate copies if it has arrived at node C before node B failed. The management of duplicate sparks is described in Section 3.5.3.

Fishing Hops

The HdpH scheduler supports fishing hops, but the HdpH-RS scheduler does not. Hops allow a thief to scrutinise a number of potential victim targets for work, before it gives up and attempts again after a random delay. A thief will transmit a fish message to a random target. If that target does not have sparks to offer, the victim will forward the fish on behalf of the thief. Each fish request is given a maximum *hop count*. That is, the number of times it will be forwarded before a `NOWORK` message is returned to the thief.

Idle nodes proactively fish for sparks on other nodes. When they send a fish, they do not send another until they receive a reply from a targeted node. The expected reply is `SCHEDULE` with a spark, or `NOWORK`. Algorithm 10 shows how a node will stop waiting for a reply when a `DEADNODE` message is received about the chosen victim.

If hops were supported, thieves may potentially be deadlocked while waiting for a fishing reply. A simple scenario is shown in Figure 3.19. A spark is fished from node A to B. Node D sends a fish to C, which is forwarded to node B. Node B receives the fish, but fails before sending a reply to D. Although D *will* receive a `DEADNODE B` message, it will not reset the fishing lock. It is expecting a reply from C, and is oblivious to the fact

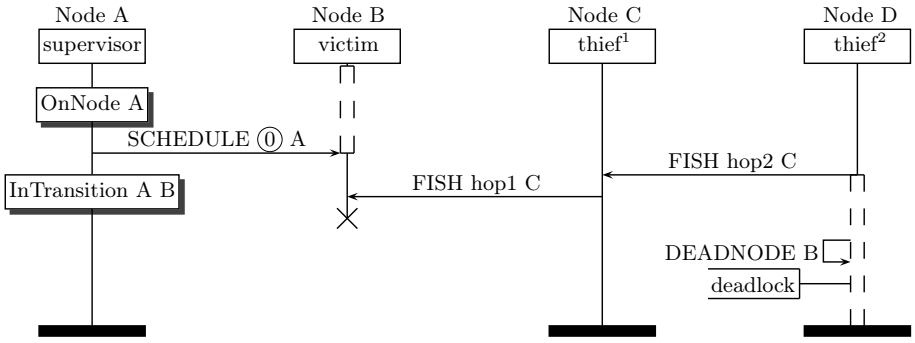


Figure 3.19: (Hypothetical) Fishing Reply Deadlock

that the fish was forwarded to B. While there could be mechanisms for supporting hops, for example fishing with timeouts, it would complicate both the work stealing algorithms (Section 3.5.4) and also the formal verification of the protocol in Chapter 4.

Guard Posts

The fishing protocol actively involves the supervisor in the migration of a spark. When a victim is targeted, it sends an authorisation request to the supervisor of a candidate local spark. The response from the supervisor indicates whether the candidate spark should be scheduled to the thief, or whether it is an obsolete spark.

The *guard post* is node state with capacity to hold one spark. Candidate sparks are moved from the sparkpool to the guard post while authorisation is pending. From there, one of three things can happen. First, the candidate spark may be scheduled to a thief if the victim is authorised to do so. Second, the candidate may be moved back into the sparkpool if authorisation is denied. Third, it may be removed from the guard post and discarded if the supervisor identifies it as an obsolete spark.

3.5.3 Duplicate Sparks

In order to ensure the safety of supervised sparks, the scheduler makes pessimistic assumptions that tasks have been lost when a node fails. If a supervisor is certain that a supervised spark was on the failed node, then it is replicated. If a supervisor believes a supervised spark to be in-flight either towards or away from the failed node during a fishing operation, again the supervised spark is replicated. The consequence is that the scheduler may create duplicates.

Duplicates of the same spark can co-exist in a distributed environment with one constraint. Older obsolete spark replicas are not permitted to migrate through work stealing, as multiple migrating copies with the same reference may potentially lead to inconsistent location tracking (Section 3.5.2). However, they *are* permitted to transmit

results to `IVar`s using `rput`. Thanks to idempotence, this scenario is indistinguishable from the one where the obsolete replica has been lost.

> "Idempotence is a correctness criterion that requires the system to tolerate duplicate requests, is the key to handling both communication and process failures efficiently. Idempotence, when combined with retry, gives us the essence of a workflow, a fault tolerant composition of atomic actions, for free without the need for distributed coordination". [70]

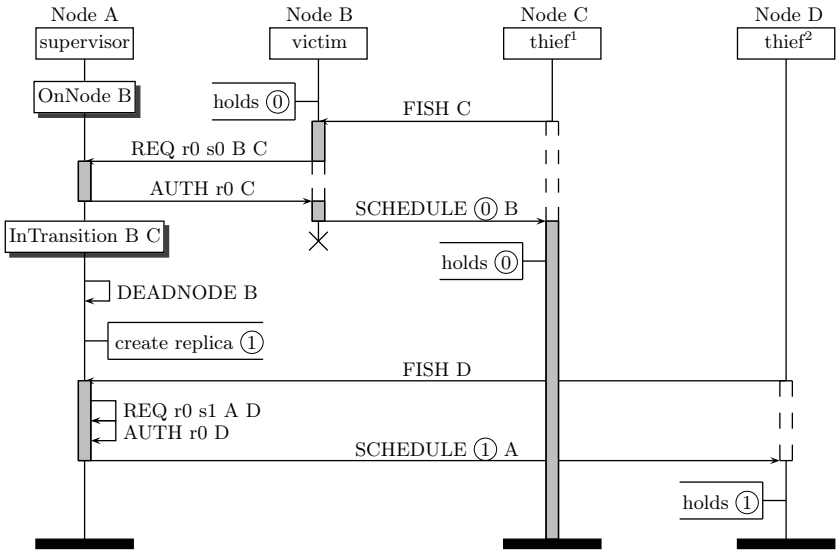


Figure 3.20: Pessimistic Scheduling that Leads to Spark Duplication

This possibility is illustrated in Figure 3.20. A supervised spark has been created with `supervisedSpawn` on node A. It has been fished by node B. During a fishing phase between B and C, B fails. Supervising node A has not yet received an `ACK` from C, and pessimistically replicates the spark locally. In this instance, the original spark did survive the failure of node B. There are now two copies of the same supervised spark in the distributed environment.

Location tracking for a task switches between two states, `OnNode` and `InTransition`, when a supervisor receives either a `ACK` and `REQ` message about the spark. The spark is identified by a pointer to an `IVar`. The strategy of replicating an in-transition task is pessimistic — the task may survive a node failure depending on which came first: a successful `SCHEDULE` transmission, or node failure detection. This requires a strategy for avoiding possible task tracking race conditions, if there exists more than one replica.

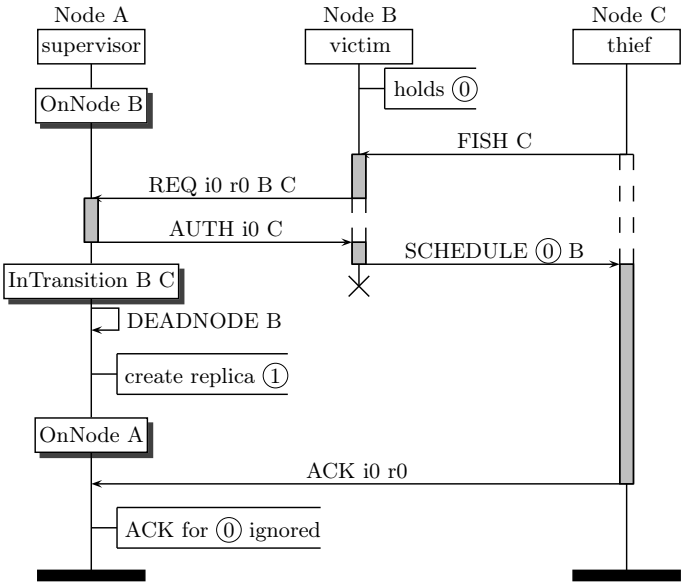


Figure 3.21: Replication of a Spark, ACK for Obsolete Ignored.

Replica Numbers in `ACK` Messages

The handling of `ACK` messages relating to obsolete replicas is illustrated in Figure 3.21. Node B holds $spark_0$, which is successfully fished to node C. The supervisor of $spark_0$ receives notification that B has failed before an `ACK` has been received from C. The pessimistic recovery strategy replicates the spark on node A as $spark_1$. When the `ACK` from C is eventually received on A about $spark_0$, it is simply ignored.

Replica Numbers in `REQ` Messages

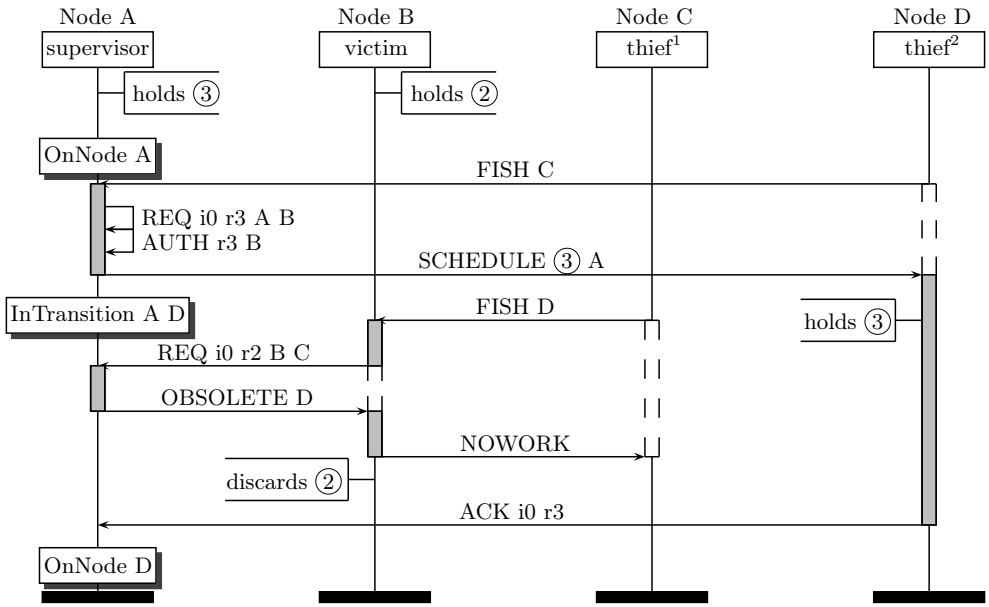


Figure 3.22: Obsolete Replicas are Discarded on Scheduling Attempts

The handling of `REQ` messages relating to obsolete replicas is illustrated in Figure 3.22. Due to two node failures that have occurred prior to this message sequence, there have been 3 replicas created from the original. Two still remain, replica 2 on node B, and replica 3 on node A. Node C successfully steals $spark_3$ from A. Node D targets B as a fishing victim. Node B requests authorisation from A, using $r2$ to identify $spark_2$ it holds. The supervisor determines that the younger $spark_3$ is in existence, and so the scheduling request for $spark_2$ is denied with an `OBSOLETE` reply. The victim node C replies to the thief node D with a `NOWORK` message, and discards $spark_2$. The HdpH-RS implementation of task replica numbers is later described in Section 5.1.1.

3.5.4 Fault Tolerant Scheduling Algorithm

This section presents the algorithms for supervised spark scheduling and fault recovery. It describes message handling for the fault tolerant fishing protocol (Section 3.5.1), how obsolete sparks are identified and discarded (Section 3.5.3), and how task migration is tracked (Section 3.5.2). Each node is proactive in their search for work with fishing (Algorithm 1), triggering a sequence of message sequences between the victim, thieving and supervising nodes as shown in Figure 3.23.

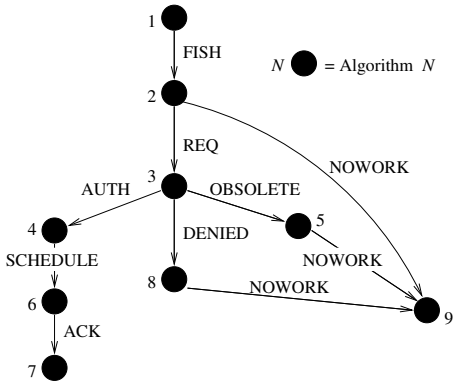


Figure 3.23: Algorithm Interaction in Fault Tolerant Algorithm

Algorithm 1 Algorithm for Proactive Fishing from a Thief

```
1: function FISH
2:     loop
3:         if not fishing then                          ▷ is there an outstanding fish
4:             isFishing ← True                         ▷ blocks fishing until victim responds
5:             thief ← myNode                           ▷ this node is thief
6:             victim ← randomNode
7:             msg ← FISH thief
8:             send target msg                          ▷ send to dead target will fail
```

Algorithm 2 shows how a node that receives a `FISH` has been targeted by a thief. A condition on line 3 checks that this node has not already been targeted by another thief

and is waiting for authorisation. If it is waiting for authorisation, then a `NOWORK` reply is sent to the thief. If it is not waiting for an authorisation, then the local sparkpool is checked for sparks. If a spark is present, then it is moved in to the guard post and an authorisation request is sent to the supervisor of that spark. Otherwise if the sparkpool is empty, a `NOWORK` is sent to the thief.

Algorithm 2 Algorithm for Handling `FISH` Messages by a Victim

PreCondition: Thief (*fisher*) is looking for work.

```
 1: function HANDLE(FISH thief)
 2:     actioned ← False
 3:     if not waitingforauth then                ▷ is there an outstanding authorisation request
 4:         if sparkpool not empty then
 5:             spark ← pop sparkpool                          ▷ pop spark from local sparkpool
 6:             guardPost ← push spark                         ▷ add spark to guard post
 7:             msg ← REQ spark.ref spark.replica myNode thief
 8:             send spark.supervisor msg                      ▷ authorisation reqest to supervisor
 9:             actioned ← True                                ▷ local spark guarded
10:     if not actioned then
11:         msg ← NOWORK
12:         send thief msg                                     ▷ inform thief of no work
```

If a victim has sparks that could be scheduled to a thief, it sends an authorisation request to a supervisor, shown in Algorithm 2. The handling of this request is shown in Algorithm 3. A guarded spark is one held in the guard post. If the location of the guarded spark is known to be in a sparkpool of the victim (Section 3.5.2), the request is granted with `AUTH`. Otherwise, if the task is believed to be in transition between two nodes, the request is rejected with `DENIED`. If the spark is obsolete, then the victim is instructed to discard it with an `OBSOLETE` message.

Algorithm 3 Algorithm for Handling `REQ` Messages by a Supervisor

PreCondition: A schedule request is sent from a victim to this (supervising) node.

```
 1: function HANDLE(REQ ref replica victim thief)
 2:     replicaSame ← compare (replicaOf ref) replica
 3:     if replicaSame then                          ▷ remote task is most recent copy
 4:         location ← locationOf ref
 5:         if location == OnNode then               ▷ supervisor knows task is in a sparkpool
 6:             update location (InTransition victim thief)
 7:             msg ← AUTH thief                                ▷ authorise the request
 8:         else if location == InTransition then
 9:             msg ← DENIED thief                              ▷ deny the request
10:     else
11:         msg ← OBSOLETE thief      ▷ remote task is old copy, ask that it is discarded
12:     send victim msg
```

When a victim that holds a spark is targeted, then it requests scheduling authorisation in Algorithm 2. If the request is granted in Algorithm 3, then a victim will receive an `AUTH` message. The handling of an authorisation is shown in Algorithm 4. It takes the

spark from the guard post on line 2, and sends it to a thief in a `SCHEDULE` message on line 4.

Algorithm 4 Algorithm for Handling `AUTH` Messages by a Victim

PreCondition: Location state on supervisor was `OnNode`.
1: **function** HANDLE($AUTH\ ref\ thief$)
2: $spark \leftarrow pop\ GuardPost$
3: $msg \leftarrow SCHEDULE\ spark$
4: **send** $thief\ msg$ ▷ send thief the spark
PostCondition: Thief will receive spark in the `SCHEDULE` message.

However, if a victim is informed with `OBSOLETE` that the spark in its guard post is an obsolete copy (Algorithm 5), it empties the guard post on line 2, and informs the thief that no work is available on line 5.

Algorithm 5 Algorithm for Handling `OBSOLETE` Messages by a Victim

PreCondition: The guarded spark was obsolete.
1: **function** HANDLE($OBSOLETE\ thief$)
2: $obsoleteSpark \leftarrow pop\ GuardPost$ ▷ discard spark in guard post
3: **remove** $obsoleteSpark$
4: $msg \leftarrow NOWORK$
5: **send** $thief\ msg$ ▷ inform thief of no work
PostCondition: Guarded spark is discarded, thief will receive `NOWORK`.

When a victim is granted permission to send a spark to a thief, then a thief will receive a `SCHEDULE` holding the spark. The handler for scheduled sparks is shown in Algorithm 6. It adds the spark to its own sparkpool on line 2, and sends an acknowledgement of its arrival to its supervisor on line 4.

Algorithm 6 Algorithm for Handling `SCHEDULE` Messages by a Thief

PreCondition: A Victim was authorised to send this node a spark in a *SCHEDULE*.
1: **function** HANDLE($SCHEDULE\ spark$)
2: **insert** $spark\ sparkpool$ ▷ add spark to sparkpool
3: $msg \leftarrow ACK\ spark.ref\ spark.replica\ myNode$
4: **send** $spark.supervisor\ msg$ ▷ send `ACK` to spark's supervisor
PostCondition: Supervisor of spark will receive an *ACK* about this spark.

A thief sends an acknowledgement of a scheduled spark to its supervisor. The reaction to this `ACK` is shown in Algorithm 7. It updates the migration tracking for this spark to `OnNode`, a state that will allow another thief to steal from the new host of the spark.

In the scenario where a `REQ` is received about a spark before an `ACK` (i.e. its migration state is `InTransition`), then the request is denied. This scenario is depicted in Figure 3.17. When a victim is denied a scheduling request, it informs the thief that no work can be offered, on line 5 of Algorithm 8.

Algorithm 7 Algorithm for Handling `ACK` Messages by a Supervisor

PreCondition: Thief receives a spark.

```
1: function HANDLE(ACK ref thief)
2:     update (locationOf ref) (OnNode thief)        ▷ set spark location to OnNode
```

PostCondition: Location state updated to `OnNode`.

Algorithm 8 Algorithm for Handling `DENIED` Messages by a Victim

PreCondition: location state on supervisor was `InTransition`.

```
1: function HANDLE(DENIED thief)
2:     spark ← popGuardPost
3:     insert spark sparkpool                        ▷ put spark back into sparkpool
4:     msg ← NOWORK
5:     send thief msg                                ▷ inform thief of no work
```

PostCondition: fisher is given no work and can fish again.

A thief will fail to steal from its chosen victim in one of two circumstances. First, because the victim has no sparks to offer (Algorithm 2). Second, because the supervisor has denied the request (Algorithm 3). A thief's reaction when a `NOWORK` message is received is shown in Algorithm 9. It removes the block that prevented the scheduler to perform on-demand fishing (Algorithm 1). The thief can start fishing again.

Algorithm 9 Algorithm for Handling `NOWORK` Messages by a Thief

PreCondition: The victim was denied its authorisation request.

```
1: function HANDLE(NOWORK)
2:     isFishing ← False
```

PostCondition: This thief can fish again.

Finally, Algorithm 10 shows the action of a node when a `DEADNODE` message is received. It corresponds to the Haskell implementation in Appendix A.6. There are four checks performed by every node when a remote node fails. First, it checks if it is waiting for a fishing reply from the dead node (line 3). Second, whether the dead node is the thief of the spark it has requested authorisation for (line 5). Third, it identifies the supervised sparks are at-risk due to the remote node failure (line 8). Fourth, it identifies the supervised threads are at-risk due to the remote node failure (line 9).

If a node is waiting for a fishing reply, it removes this block and no longer waits (line 3). It is free to fish again. If the node is a fishing victim of the failed node (line 5), then the spark in the guard post is popped back in to the sparkpool. All at-risk (Section 3.5.2) sparks are replicated and added to the local sparkpool. These duplicates can be fished again for load-balancing (line 11). All at-risk threads are replicated and are converted and executed locally (line 13). The Haskell implementation of spark and thread replication is in Appendix A.7.

Algorithm 10 Algorithm for Handling `DEADNODE` Messages by All Nodes

PreCondition: A remote node has died.

```
 1: function HANDLE(DEADNODE deadNode)
 2:     remove deadNode from distributed VM
 3:     if waitingFishReplyFrom == deadNode then
 4:         isFishing ← False                          ▷ stop waiting for reply from dead node
 5:     if thiefOfGuardedSpark == deadNode then
 6:         spark ← pop guardPost
 7:         insert spark sparkpool                     ▷ put spark back in to sparkpool
 8:     VulnerableSparks ← (supervised sparks on deadNode)        ▷ at-risk sparks
 9:     VulnerableThreads ← (supervised threads on deadNode)      ▷ at-risk threads
10:     for all s ∈ VulnerableSparks do
11:         insert s sparkpool                         ▷ Replicate potentially lost supervised spark
12:     for all t ∈ VulnerableThreads do
13:         insert t threadpool          ▷ Replicate potentially lost thread: convert & execute locally
```

PostCondition: All at-risk supervised sparks and threads are recovered.

3.5.5 Fault Recovery Examples

This section introduces the fault tolerance mechanisms of the HdpH-RS scheduler. The task replication and failure detection techniques are similar to those used in the supervised workpools, demonstrated in Appendix A.1.2. When the `supervisedSpawn` and `supervisedSpawnAt` primitives are used (Section 3.3.2), the HdpH-RS scheduler guarantees task execution, provided that the caller and the root node (if they are distinct) do not die. This section presents a series of diagrammatic explanations of scheduling behaviour in the presence of faults. Section 3.4 describes the operational semantics that formalise these behaviours, and Section 4.3.5 models the message passing in the scheduler that implements the scheduling.

A simple HdpH-RS system architecture is shown in Figure 3.24. This depicts a supervisor node and three worker nodes. Each node has a sparkpool and a threadpool. Every node has tasks residing in both the sparkpool and the threadpool. Tasks in sparkpools can migrate to other sparkpools using load balancing. Tasks are moved into threadpools through one of two actions — either they have been remotely scheduled with `supervisedSpawnAt` or a spark has been converted to a thread by the scheduler (see the transition `convert_spark` in Section 3.4).

Recovering Sparks

This section describes the scenario of the `supervisedSpawn` primitive being used to schedule 6 sparks, with a network of 4 nodes. After spawning there will be 6 sparks in the *sparkpool* of the supervisor node, shown in Figure 3.25. For the purposes of illustration, the 3 workers fish continually in order to hold more than one spark.

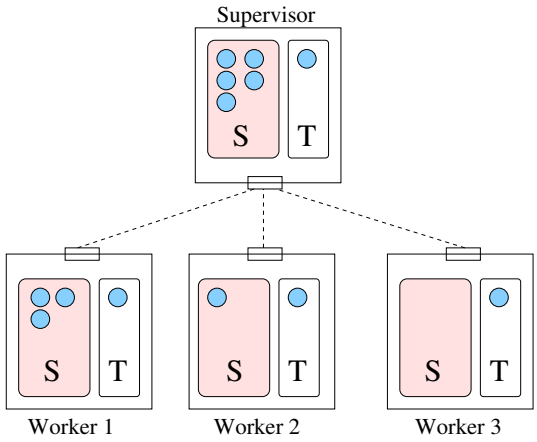


Figure 3.24: Simple HdpH-RS System Architecture

Work stealing balances the sparks across the architecture, shown in Figure 3.26. Worker 1 fails, which is detected by the supervisor. The recovery action of the supervisor is to replicate sparks 3 and 6, and add them to the local sparkpool, shown in Figure 3.27. Finally, these recovered sparks may be once again fished away by the two remaining worker nodes, shown in Figure 3.28.

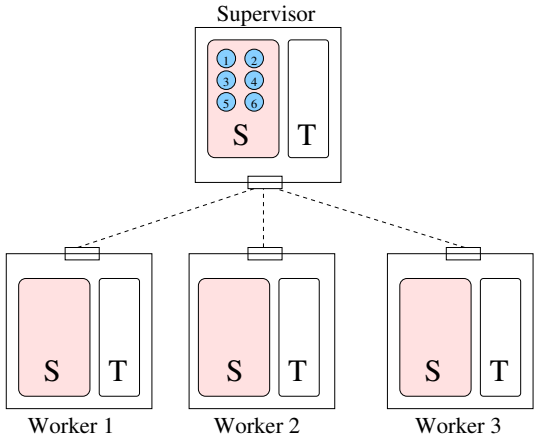


Figure 3.25: Six tasks are lazily scheduled by the supervisor node

Recovering Threads

The scenario in Figure 3.29 shows a supervisor node eagerly distributing 6 tasks across 3 worker nodes with round robin scheduling with `supervisedSpawnAt`. The tasks are never placed in the supervisor's sparkpool or threadpool. When worker 1 dies, the supervisor immediately replicates a copy of threads 1 and 4 into its own threadpool, to be evaluated locally, depicted in Figure 3.30.

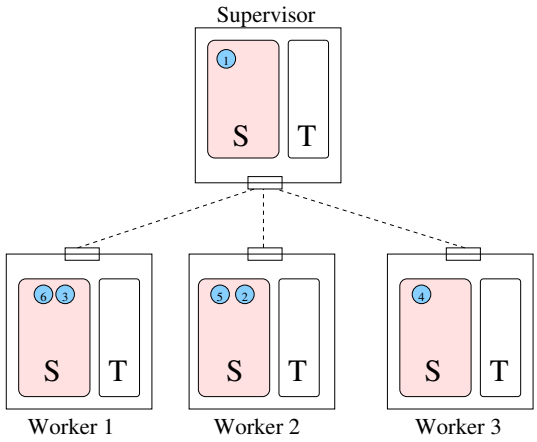


Figure 3.26: Six tasks are fished equally by 3 worker nodes

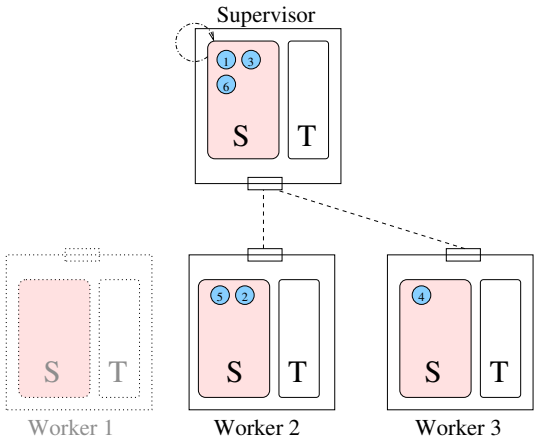


Figure 3.27: A worker node fails, and copies of lost tasks are rescheduled by the supervisor

Simultaneous Failure

There are failure scenarios whereby the connection between the root node and multiple other nodes may be lost. Communication links may fail by crashing, or by failing to deliver messages. Combinations of such failures may lead to partitioning failures [46], where nodes in a partition may continue to communicate with each other, but no communication can occur between sites in different partitions.

There are two distinguished connected graphs in the distributed HdpH-RS virtual machine. First is the networking hardware between hosts. Sockets over TCP/IP is used on Ethernet networking infrastructures in HdpH-RS (Section 5.5) to send and receive messages. The maximum size of this connected graph is fixed, hosts cannot be added during runtime.

The second graph connects tasks to futures. Recall from Section 3.3.2 that futures are created with the spawn family of primitives. A task may be decomposed in to smaller tasks, creating futures recursively.

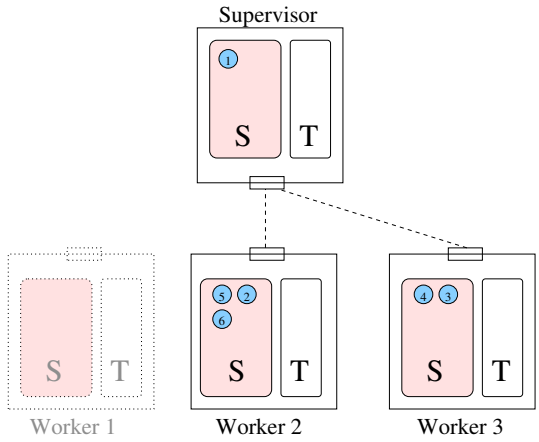


Figure 3.28: The rescheduled tasks are once again fished away

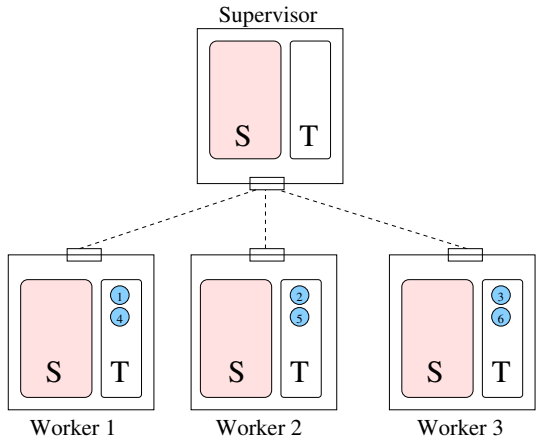


Figure 3.29: Six tasks are eagerly scheduled as threads to 3 worker nodes

A simple graph expansion of futures is shown in Figure 3.31. All nodes in a dotted area are connected in a network. Nodes A and B are connected. Node A takes the role of the root node and starts the computation, which splits the program into 30 tasks. During runtime, 5 unevaluated tasks are stolen by node B over the network connection. These 5 tasks are expanded in to 10, so node B holds 10 tasks. The program in total has therefore expanded to a graph of 35 futures. The key point is that in both the absence and presence of faults, this program will always expand to 35 futures.

A slightly more complicated decomposition is in Figure 3.32. This program is expanded to a graph of 54 futures in total, over 5 nodes including the root node.

The failure scenario is shown in Figure 3.33. The network is split in to two partitions, one comprised of nodes A, B and C, and the other with nodes D and E. A *lost* partition is one that no longer includes the root node A. The static network connection from the root node A to both D and E are lost, and so D and E are zombie nodes. Despite the fact that the connection with the root node was lost by D and E simultaneously, notification of connection loss from these nodes will arrive sequentially at A, B and C. Nodes D

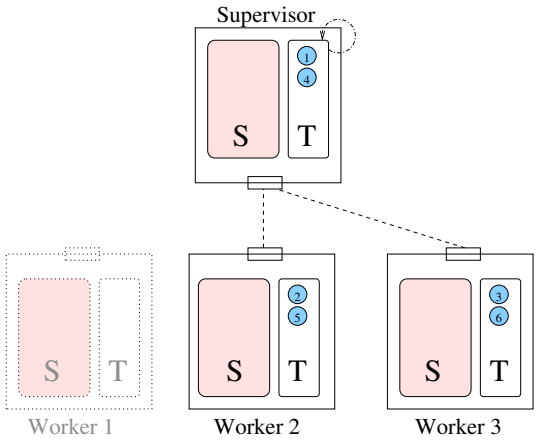


Figure 3.30: Copies of the two lost tasks are converted to threads on the supervisor node

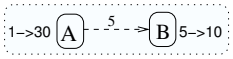


Figure 3.31: Graph Expansion of Tasks

and E will receive notification that connection with root node A has been lost, and will terminate as they know they can no longer play a useful role in the execution of the current job.

The recovery of tasks is shown in Figure 3.34. Nodes A, B and C check whether these lost connections affect the context of the futures they host locally. Node A concludes that it is completely unaffected by the connection loss. Node B concludes that it is affected by the loss of node D, and must recover 3 tasks. Node C concludes that it is affected by the loss of node E, and must recover 8 tasks. These tasks will once again expand from 3 to 6, and 8 to 14, respectively.

The scenario in this section demonstrates that in the presence of network failure, incurring the loss of connection from the root node to two nodes, the program executing on the partition containing the root node expands to 54 futures — the same as failure-free evaluation.

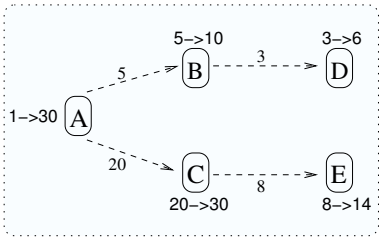


Figure 3.32: Graph Expansion of Tasks over 5 Nodes

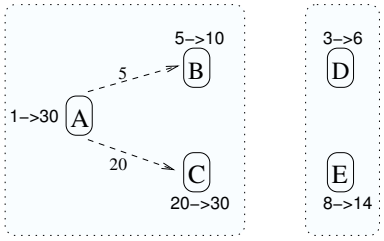


Figure 3.33: Network Partition, Leaving Nodes D & E Isolated

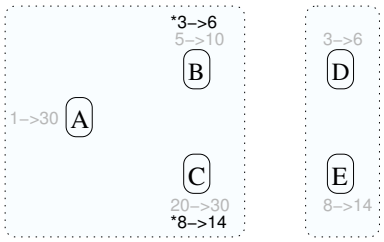


Figure 3.34: Recovering Tasks from Nodes D & E

3.6 Summary

This chapter has presented the language and scheduling design of a HdpH-RS. The next chapter presents a Promela model of the scheduling algorithm from Section 3.5.4. A key property is verified using the SPIN model checker. This property states that a supervised future (Section 3.3.1) is eventually filled despite all possible combinations of node failure. Chapter 5 then presents a Haskell implementation of the HdpH-RS programming primitives and the verified reliable scheduling design.

Chapter 4

The Validation of Reliable Distributed Scheduling for HdpH-RS

Chapter 3 presents the design of HdpH-RS — the fault tolerant programming primitives `supervisedSpawn` and `supervisedSpawnAt` (Section 3.3.2) supported by a reliable scheduler (Section 3.5). This chapter validates the critical reliable properties of the scheduler. The SPIN model checker is used to ensure that the HdpH-RS scheduling algorithms (Section 3.5.4) honour the small-step semantics on states (Section 3.4), supervising sparks in the absence and presence of faults.

Model checking has been shown to be an effective tool in validating the behaviour of fault tolerant systems, such as embedded spacecraft controllers [143], reliable broadcasting algorithms [91], and fault tolerant real-time startup protocols for safety critical applications [57]. Model checking has previously been used to eliminate non-progress cycles of process scheduling in asynchronous distributed systems [83].

Fault tolerant distributed algorithms are central to building reliable distributed systems. Due to the various sources of non-determinism in faulty systems, it is easy to make mistakes in the correctness arguments for fault tolerant distributed systems. They are therefore natural candidates for model checking [91]. The HdpH-RS scheduler must hold reliability properties when scaled to complex non-deterministic distributed environments:

1. **Asynchronous message passing** Causal ordering [99] of asynchronous distributed scheduling events is not consistent with wall-clock times. Message passing between nodes is asynchronous and non-blocking, instead writing to channel buffers. Because of communication delays, the information maintained in a node concerning its neighbours' workload could be outdated [186].

2. **Work stealing** Idle nodes attempt to steal work from overloaded nodes. To recover tasks in the presence of failure, a supervisor must be able to detect node failure and

must always know the location of its supervised tasks. The asynchronous message passing from (1) complicates location tracking. The protocol for reliably relocating supervised tasks between nodes in the presence of failure is intricate, and model checking the protocol increases confidence in the design.

3. **Node failure** Failure is commonly detected with timeouts or ping-pong protocols (Section 2.2.3). The Promela abstraction models node failure, and latency's of node failure detection.

The model of the HdpH-RS scheduler shows that by judiciously abstracting away extraneous complexity of the HdpH-RS implementation, the state space can be exhaustively searched for validating a key reliability requirement. The key HdpH-RS reliable scheduling property is validated with SPIN [83] [84] in Section 4.4, by defining a corresponding safety property in linear temporal logic. Bugs were fixed in earlier versions of the Promela model, when violating system states were identified. An example of bug finding using this iterative implementation of HdpH-RS using model checking is described in Section 4.6.

The motivation for modeling work stealing in asynchronous environments is given in Section 4.1. The scope of the Promela abstraction of the HdpH-RS scheduler is in Section 4.2. The model of the work stealing scheduler is in Section 4.3. The use of linear temporal logic for expression a key reliability property is shown in Section 4.4. The SPIN model checker to exhaustively search the model's state space to validate that the reliability property holds on all reachable states. The SPIN model checking results are in Section 4.5.

4.1 Modeling Asynchronous Environments

4.1.1 Asynchronous Message Passing

Most message passing technologies in distributed systems can be categorised in to three classes [168]: unreliable datagrams, remote procedure calls and reliable data streams. *Unreliable datagrams* discard corrupt messages, but do little additional processing. Messages may be lost, duplicated or delivered out of order. An example is UDP [131]. In *remote procedure calls*, communication is presented as a procedure invocation that returns a result. When failure does occur however, the sender is unable to distinguish whether the destination failed before or after receiving the request, or whether the network has delayed the reply. *Reliable data streams* communicate over channels that provide flow control and reliable, sequenced message delivery. An example is TCP [133].

A TCP connection in the absence of faults provides FIFO ordering between two nodes. The relationship between messaging events can be described as *causal ordering*. Causal ordering is always consistent with the actual wall-clock times that events occur. This can be written as $send(m_1) \rightarrow send(m_2)$ [99], where $\rightarrow$ means happened-before. The ordering property of TCP guarantees that $recv(m_1)$ occurs before $recv(m_2)$ on the other end of the connection. This ordering guarantee is not sufficient in distributed systems that have *multiple* TCP connections. The latency of TCP data transfer is well known [29], for example due to memory copying with kernel buffers, heterogeneous network latency, and TCP data transfer latency [29].

HdpH-RS uses a network abstraction layer [44] that assigns an *endpoint* to each node. An endpoint is a mailbox that consumes messages from multiple connections established with other nodes. Causal ordering of messaging events is no longer consistent with wall-clock time. This potentially leads to *overtaking* on two separate TCP connections.

Take a simple architecture with three nodes A, B and C. If A is connected with B on dual connection c_1 and to C on dual connection c_2, then the endpoint E_A on node A is defined as $E_A = \{c_1, c_2\}$. Nodes B and C send messages to E_A in the causal order $c_1.send(m_1) \rightarrow c_2.send(m_2)$. Ordering of events $c_1.recv(m_1)$ and $c_2.recv(m_2)$ at E_A is unknown. The HdpH-RS work stealing protocol enforces a certain order of events, and message responses are determined by task location state (Section 3.5.4).

4.1.2 Asynchronous Work Stealing

Work stealing for balancing load is introduced in Section 3.2, describing how nodes inherit thief, victim and supervisory roles dynamically. Location tracker messages sent by a thief and a victim with respect to a spark migrating between the two may be received in any order by the spark's supervisor due to asynchronous message passing (Section 4.1.1).

The HdpH-RS fishing protocol gives the control of spark migration to the supervisor. The fishing protocol (Section 3.5.1) is abstracted in Promela in Section 4.2. The protocol handles any message sequence from thieves and victims to ensure that task location tracking is never invalidated. The Promela model honours the small-step transition rules `migrate_supervised_spark` and `recover_supervised_spark` (Section 3.4.3) for migrating and replicating supervised sparks shown in Section 4.3.3. The `kill_node` transition rule in the small-step semantics can be triggered at any time as described in Section 4.3.2. This is modelled in Promela with a non-deterministic unconditional choice that workers can take (Section 4.3.1).

4.2 Promela Model of Fault Tolerant Scheduling

4.2.1 Introduction to Promela

Promela is a meta-language for building verification models, and the language features are intended to facilitate the construction of high-level abstractions of distributed systems. It is not a systems implementation language. The emphasis in Promela abstraction is synchronisation and coordination with messages, rather than computation. It supports for example, the specification of non-deterministic control structures and it includes primitives for process creation, and a fairly rich set of primitives for interprocess communication. Promela is *not* a programming language [84], and so does not support functions that returns values and function pointers. This chapter verifies the fault tolerant scheduler from Section 3.5. Chapter 5 presents the Haskell *implementation* of the verified scheduler and HdpH-RS programming primitives. The SPIN analyser is used to verify fractions of process behaviour, that are considered suspect [89].

Temporal logic model checking is a method for automatically deciding if a finite state program satisfies its specification [37]. Since the size of the state space grows exponentially with the number of processes, model checking techniques based on explicit state enumeration can only handle relatively small examples [36]. When the number of states is large, it may be very difficult to determine is such a program is correct. Hence, the infinite state space of the real HdpH-RS scheduler is abstracted to be a small finite model that SPIN can verify.

The HdpH-RS scheduler has been simplified to its core supervision behaviours that ensure supervised task survival. The model includes 1 supervisor, 3 workers and 1 supervised spark. The abstract model is sufficiently detailed to identify real bugs in the implementation e.g. the identified bug described in Section 4.6.

> SPIN is not a simulation or an application environment, it is a formal verification environment. Is this really a model that will comply with the correctness requirements only if the number of channels is 1,000? If so, I would consider that a design error in itself. *Gerard J. Holzmann* [90]

Constructing Promela Models

Promela programs consist of processes, message channels, and variables. Processes are global objects that represent the concurrent nodes in HdpH-RS. Message channels for the supervisor and workers are declared globally. The variables used in the propositional symbols in LTL formulae (Section 4.4) are declared globally. Other variables are declared

locally within the process. Whist processes specify behaviour, channels and global variables define the environment in which the processes run. A simple Promela model is shown in Listing 4.1.

```
1  typedef Sparkpool {
2    int spark_count=0; /* #spark replicas */
3    int spark=0;       /* highest sequence number */
4  }
5
6  chan chans[4] = [10] of {mtype,int,int};
7
8
9
10 inline report_death(me){ /* .. */ }
11
12
13 active proctype Supervisor() {
14   int thief_pid, victim_pid, seq_n;
15
16
17
18   if
19   :: chans[0].inChan ? ACK(thief_pid,seq_n) ->
20        /* .. */
21   :: chans[0].inChan ? REQ(victim_pid,thief_pid) ->
22        /* .. */
23   fi;
24
25   atomic { /* .. */ }
26 }
```

User defined data types.

Declaring & initialising message passing channel with a buffer capacity for 10 messages.

Stylized version of a macro.

Instantiate initial Supervisor process.

If more than one guard statement is executable, one of them will be selected non-deterministically.

Code fragment executed indivisibly.

Listing 4.1: Example Promela Model Construction

The Promela abstraction of the HdpH-RS scheduler is detailed in Section 4.2.3. The full Promela implementation is in Appendix A.3. The Promela terminology defines *processes* as isolated units of control, whose state can only be changed by other processes through message passing. This chapter deviates by using *nodes* as a synonym for processes, in order to be consistent with the HdpH-RS terminology.

4.2.2 Key Reliable Scheduling Properties

The SPIN model checker is used to verify key reliable scheduling properties of the algorithm designs from Section 3.5.4. SPIN accepts design specification written in the verification language Promela, and it accepts correctness claims specified in the syntax of standard Linear Temporal Logic (LTL) [130]. Section 4.5 shows the LTL formula used by SPIN to verify the Promela abstraction of HdpH-RS scheduling.

The correctness claims guarantee supervised spark evaluation. This is indicated by filling its corresponding supervised future (the `IVar`) on the supervising node. The first is a counter property and is used to ensure the Promela abstraction does model potential failure of any or all of the mortal worker nodes:

1. **Any or all worker nodes may fail** To check that the model potentially kills one or more mortal workers, SPIN is used to find counter-example executions when one of the workers terminates, which it is trivially able to do after searching 5 unique states (Section 4.5.1).

Two further properties are used to exhaustively verify the absence of non-desirable states of the `IVar` on the supervisor node:

1. **The IVar is empty until a result is sent** Evaluating a task involves transmitting a value to the supervisor, the host of the `IVar`. This property verifies that the `IVar` cannot be full until one of the nodes has transmitted a value to the supervisor. The absence of a counter system state is verified after exhaustively searching 3.66 million states (Section 4.5.2).

2. **The IVar is eventually always full** The `IVar` will eventually be filled by either a remaining worker, or the supervisor. This is despite the failure of any or all worker nodes. Once it is full, it will always be full because there are no operations to remove values from `IVar`s in HdpH-RS. The absence of a counter system state is verified after exhaustively searching 8.22 million states (Section 4.5.2).

4.2.3 HdpH-RS Abstraction

The model considers tasks scheduled with `supervisedSpawn` in HdpH-RS — modeling the tracking and recovery of supervised sparks. The location of threads scheduled with `supervisedSpawnAt` is always known i.e. the scheduling target. This would not elicit race conditions on location tracking messages `REQ` and `ACK`, and are therefore not in the scope of the model. The Promela model is a partial abstraction that encapsulates behaviours necessary for guaranteeing the evaluation of supervised sparks. There are six characteristics of the HdpH-RS scheduler in the Promela model:

1. **One immortal supervisor** that initially puts a spark into its local sparkpool. It also creates spark replicas when necessary (item 6).

2. **Three mortal workers** that attempt to steal work from the supervisor and each other. Failure of these nodes is modeled by terminating the Promela process for each node.

3. **Computation** of a spark may happen at any time by any node that holds a copy of the spark. This simulates the execution of the spark, which would invoke an `rput` call to fill the `IVar` on the supervisor. It is modeled by sending a `RESULT` message to

the supervisor. This message type is not in HdpH-RS, rather it mimics `PUSH` used by `rput` to transmit a value to an `IVar` in HdpH-RS.

4. **Failure** of a worker node means that future messages to it are lost. The `kill_node` transition rule is modeled with a non-deterministic suicidal choice any of the three worker nodes can make. This choice results in a node asynchronously broadcasting its death to the remaining healthy nodes and then terminating. Failure detection is modeled by healthy nodes receiving `DEADNODE` messages.

5. **Asynchronicity** of both message passing and failure detection is modeled in Promela using buffered channels. Buffered channels model the buffered FIFO TCP connections in HdpH-RS.

6. **Replication** is used by the supervisor to ensure the safety of a potentially lost spark in the presence of node failure. The model includes spark replication from algorithm 10 in Section 3.5.4, honouring the `recover_supervised_spark` small-step transition rule in Section 3.4.3. Replication numbers are used to tag spark replicas in order to identify obsolete spark copies. Obsolete replica migration could potentially invalidate location records for a supervised spark, described in Section 3.5.3. Therefore, victims are asked to discard obsolete sparks, described in Algorithm 5 of Section 3.5.4.

Two scheduling properties in Section 4.4.1 state that a property must eventually be true. The formula $\Box\,(ivar\_empty\ \mathcal{U}\ any\_result\_sent)$ in Section 4.4.1 is a *strong until* connective and verifies two properties of the model. First, that the *ivar_empty* property must hold until at least *any_result_sent* is true. Second, that *any_result_sent* is true in some future state (the *weak until* connective does not demand this second property). The formula $\Diamond\,\Box\,ivar\_full$ demands that the `IVar` on the supervisor is eventually always full.

Without any deterministic choice of sending a `RESULT` message to the supervisor, the three thieving worker nodes could cycle through a sequence of work stealing messages, forever passing around the spark and each time visiting an identical system state. The SPIN model checker identified this cyclic trace in an earlier version of the model. These cycles contradict the temporal requirements of the *strong until* and *eventually* connectives in the two properties above.

Determinism is introduced to the model by ageing the spark through transitions of the model. The age of the spark is zero at the initial system state. Each time it is scheduled to a node, its age is incremented. Moreover, each time it must be replicated by the

supervisor its age is again incremented. When the age of the spark reaches 100, all nodes are forced to make a deterministic choice to send a `RESULT` message to the supervisor if they hold a replica or else the next time they do. This models the HdpH-RS assumption that a scheduler will eventually execute the spark in a sparkpool.

4.2.4 Out-of-Scope Characteristics

Some aspects of the HdpH-RS scheduler design and implementation are not abstracted in to the Promela model, because they are not part of the fault tolerance actions to guarantee that an `IVar` will be written to.

1. **Multiple IVars** The model involves only *one* `IVar` and one supervised spark, which may manifest into multiple replicas — one active and the rest obsolete. Multiple `IVar`s are not modeled.

2. **Non-supervised sparks** Only *supervised* sparks created with `supervisedSpawn` are modeled, while unsupervised sparks are not. Non-supervised sparks are created by calls to `spawn` (Section 3.3.2), and create sparks that are intentionally not resilient to faults, and by-pass the fault tolerant fishing protocol.

3. **Threads** Threads are created with `spawnAt` and `supervisedSpawnAt`. Section 3.3.2 describes why eagerly placed threads are more straight forward to supervise. Once they are transmitted to a target node, they do not migrate.

4.3 Scheduling Model

4.3.1 Channels & Nodes

Nodes interact with message passing. Using Promela syntax, nodes receive messages with `?`, and send messages with `!`. A simple example is shown in Figure 4.1. Node A sends a message `FOO` with `!` to a channel that node B receives messages on. Node B reads the message from the channel with `?`. The channels in the Promela model of HdpH-RS are asynchronous, so that messages can be sent to a channel buffer, rather than being blocked waiting on a synchronised participatory receiver. This reflects the data buffers in TCP sockets, the transport protocol in HdpH-RS.

Channels

There are four channels in the model, one for each of the four nodes. They are globally defined as shown on line 1 of Listing 4.2. The channels can store up to ten messages, which

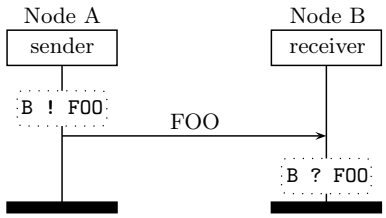


Figure 4.1: Message Passing in Promela

is more than strictly required in this model of four nodes where the protocol enforces nodes to wait for responses for each message sent. Each message consists of four fields: a symbolic name and three integers. The symbolic name is one of the protocol messages e.g. `FISH`, and the three integers are reserved for process IDs and replica numbers. A `null` macro is defined as -1, and is used in messages when not all fields are needed. For example, `REQ` message uses three fields to identify the victim, the thief, and the replica count of the targeted spark. The `ACK` message however only used to identify the thief and the replica number, so `null` is used in place of the last field. The supervisor node is instantiated in the initial system state (line 3). It starts the three workers (lines 4 to 6), passing values 0, 1 and 2 telling each worker which channel to consume. The supervisor node consumes messages from channel `chans[3]`.

```
1  chan chans[4] = [10] of {mtype, int , int , int } ;
2
3  active proctype Supervisor() {
4    run Worker(0);
5    run Worker(1);
6    run Worker(2);
7    /* omitted */
8  }
9
10 proctype Worker(int me) { /* consume from chans[me] channel */ }
```

Listing 4.2: Identifying Node Channels

Supervisor Node

The supervisor is modeled as an *active* `proctype`, so is instantiated in the initial system state. The supervisor executes repetitive control flow that receives work stealing messages from worker nodes and authorisation messages from the supervisor, shown in Listing 4.3. The spark is created on line 5, and the workers are started on line 9. The underlying automaton is a message handling loop from `SUPERVISOR_RECEIVE` (line 11). The exception is when the spark has aged beyond 100 (line 13), in which case a `RESULT` message is sent to itself. The label `SUPERVISOR_RECEIVE` is re-visited after the non-deterministic

message handling choice (line 32), and is only escaped on line 29 if a `RESULT` message has been received. In this case the `IVar` becomes full and the supervisor terminates.

```
1  active proctype Supervisor() {
2    int thiefID, victimID, deadNodeID, seq, authorizedSeq, deniedSeq;
3
4    atomic {
5      supervisor.sparkpool.spark_count = 1;
6      spark.context = ONNODE;
7      spark.location.at = 3;
8    }
9    run Worker(1); run Worker(2); run Worker(3);
10
11 SUPERVISOR_RECEIVE:
12           /* deterministic choice to send RESULT to itself once spark age exceeds 100 */
13   if  :: (supervisor.sparkpool.spark_count > 0 && spark.age > maxLife) →
14           chans[3] ! RESULT(null,null,null);
15       :: else →
16           if   /* non-deterministic choice to send RESULT to itself */
17             :: (supervisor.sparkpool.spark_count > 0) →
18                chans[3] ! RESULT(null,null,null);
19
20                /* otherwise receive work stealing messages */
21             :: chans[3] ? FISH(thiefID, null,null) → /*  fish request, Listing 4.10 */
22             :: chans[3] ? REQ(victimID, thiefID, seq) → /* schedule request, Listing 4.11 */
23             :: chans[3] ? AUTH(thiefID, authorizedSeq, null) → /* request response, Listing 4.12*/
24             :: chans[3] ? ACK(thiefID, seq, null) → /* spark arrival ack, Listing 4.14 */
25             :: chans[3] ? DENIED(thiefID, deniedSeq,null) → /* request response, Listing 4.15 */
26             :: chans[3] ? DEADNODE(deadNodeID, null, null) → /* notification, Listing 4.18 */
27             :: chans[3] ? RESULT(null, null, null) →
28                supervisor.ivar = 1;
29                goto EVALUATION_COMPLETE;
30            fi;
31   fi;
32 goto SUPERVISOR_RECEIVE;
33
34 EVALUATION_COMPLETE:
35 }
```

Listing 4.3: Repetitive Control Flow Options for Supervisor

Worker Nodes

Each worker executes repetitive control flow that receives work stealing message from worker nodes and authorisation messages from the supervisor, shown in Listing 4.4. The underlying automaton is a message handling loop from `WORKER_RECEIVE` (line 4). The exception is when the spark has aged beyond 100 (line 6), in which case a `RESULT` message is sent to the supervisor. Otherwise the control flow takes one of three non-deterministic choices. First, the node may die. Second, it may send a `RESULT` message to the supervisor if it holds a replica. Third, it may receive a work stealing message from a work or scheduling request response from the supervisor. The `WORKER_RECEIVE` label is re-visited after the non-deterministic message handling choice (line 42), and is only escaped if it has died (line 10) or the `IVar` on the supervisor is full. In either case the worker terminates.

```
1  proctype Worker(int me) {
2    int thiefID, victimID, deadNodeID, seq, authorisedSeq, deniedSeq;
3
4  WORKER_RECEIVE:
5    if   /* deterministic choice to send RESULT to supervisor once spark age exceeds 100 */
6      :: (worker[me].sparkpool.spark_count > 0 && spark.age > maxLife) →
7         atomic {
8           worker[me].resultSent = true;
9           chans[3]  ! RESULT(null,null,null);
10          goto END;
11        }
12
13     :: else →
14        if
15          :: skip →  /* die */
16             worker[me].dead = true;
17             report_death(me); /* Listing 4.5 */
18             goto END;
19
20             /* non-deterministic choice to send RESULT to supervisor */
21          :: (worker[me].sparkpool.spark_count > 0) →
22               chans[3] ! RESULT(null,null,null);
23
24             /* conditions for pro-active fishing */
25          :: (worker[me].sparkpool.spark_count == 0
26              && (worker[me].waitingFishReplyFrom == -1)
27              && spark.age < (maxLife+1)) →  /* go fishing */
28
29             /* otherwise receive work stealing messages */
30          :: chans[me] ? FISH(thiefID, null, null) → /* fish request, Listing 4.10 */
31          :: chans[me] ? AUTH(thiefID, authorisedSeq, null) → /* request response, Listing 4.12 */
32          :: chans[me] ? SCHEDULE(victimID, seq, null) → /* recv spark, Listing 4.13 */
33          :: chans[me] ? DENIED(thiefID, deniedSeq, null) → /* request response, Listing 4.15 */
34          :: chans[me] ? NOWORK(victimID, null, null) → /* fish unsuccessful, Listing 4.16 */
35          :: chans[me] ? OBSOLETE(thiefID, null, null) → /* task obsolete, Listing 4.17 */
36          :: chans[me] ? DEADNODE(deadNodeID, null, null) → /* notification, Listing 4.18 */
37        fi;
38   fi;
39
40   if   /* if the IVar on the supervisor if full then terminate */
41     :: (supervisor.ivar == 1) → goto END;
42     :: else → goto WORKER_RECEIVE;
43   fi;
44
45 END:
```

Listing 4.4: Repetitive Control Flow Options for a Worker

4.3.2 Node Failure

Failure is modeled by a non-deterministic choice that nodes can make at each iteration of the repetition flow in the `Worker` definition in Listing 4.4. A node can choose to die on line 15. This sets the `dead` value to `true` for the node, the `report_death` macro is invoked, and the repetition flow is escaped with `goto END` on line 18 which terminates the process.

The `report_death` definition is shown in Listing 4.5. The HdpH-RS transport layer sends `DEADNODE` messages to the scheduler message handler on each node when a connection with a remote node is lost. The `report_death` macro takes an integer `me` on line 1 which is used to identify by other nodes to identify the failed node, and sends a

```
1  inline report_death(me){
2    chans[0] ! DEADNODE(me, null, null) ;
3    chans[1] ! DEADNODE(me, null, null) ;
4    chans[2] ! DEADNODE(me, null, null) ;
5    chans[3] ! DEADNODE(me, null, null) ; /* supervisor */
6  }
```

Listing 4.5: Reporting Node Failure

```
1  typedef Sparkpool {
2     int spark_count; /* #sparks in pool */
3     int spark;       /* highest #replica */
4  };
```

Listing 4.6: Sparkpool State

```
1  mtype = { ONNODE , INTRANSITION };
2  typedef Spark {
3    int highestReplica=0;
4    Location location;
5    mtype context=ONNODE;
6    int age=0;
7  }
8
9  typedef Location
10 {
11   int from;
12   int to;
13   int at=3;
14 }
```

Listing 4.7: Spark State

```
1  typedef SupervisorNode {
2    Sparkpool sparkpool;
3    bool waitingSchedAuth=false;
4    bool resultSent=false;
5    bit ivar=0;
6  };
```

Listing 4.8: Supervisor State

```
1  typedef WorkerNode {
2    Sparkpool sparkpool;
3    int waitingFishReplyFrom;
4    bool waitingSchedAuth=false;
5    bool resultSent=false;
6    bool dead=false;
7    int lastTried;
8  };
```

Listing 4.9: Worker State

Figure 4.2: State Abstraction in Promela Model

`DEADNODE` message to the other three nodes including the supervisor. Their reaction to this message is shown in Section 4.3.5. This macro is not executed atomically, modeling the different failure detection latencies on each HdpH-RS node. SPIN is therefore able to search through state transitions whereby a node failure is only partially detected across all nodes.

4.3.3 Node State

Sparkpool

The supervisor and worker nodes each have a local sparkpool. The state of a sparkpool is in Listing 4.6. The sparkpool capacity in the model is 1. The sparkpool is either empty or it holds a spark. When it holds a spark, its replication number is used to send messages to the supervisor: to request scheduling authorisation in a `REQ` message, and confirm receipt of the spark with an `ACK` message.

The spark's Location is stored in `location` and `context` on lines 4 and 5 of Listing 4.7, which are modified by the supervisor when `REQ` and `ACK` messages are received. The location context of the supervised spark is either `ONNODE` or `INTRANSITION` (Section 3.5.2). The most recently allocated replica number is held in `highestReplica` on line 3, and is initially set to 0. The age of the spark on line 6 is initially set to 0, and is incremented when the spark is scheduled to another node or when it is replicated.

The actual expression in the spark is not modeled. The indistinguishable scenario when an `IVar` is written either once or multiple times is demonstrated with executions through the operational semantics in Section 3.4.4. Any node, including the supervisor, may transmit a result to the supervisor if it holds a spark copy. As such, a spark is simply represented as its replication count (line 3).

Supervisor State

The local state of the supervisor is shown in Listing 4.8. In the initial system state, it adds the spark to its sparkpool (line 2), which may be fished away by a worker node. To minimise the size of the state machine, the supervisor does not try to steal the spark or subsequent replicas once they are fished away. The `IVar` is represented by a bit on line 5, 0 for empty and 1 for full. Lastly, a `waitingSchedAuth` (line 3) is used to reject incoming `REQ` messages, whilst it waits for an `AUTH` from itself if it is targeted by a thief.

An example of modifying location tracking with the `migrate_supervised_spark` rule (Section 3.4.3) is shown in Figure 4.3. It is a more detailed version of the fault tolerant fishing protocol from Figure 3.16 of Section 3.5.2. The Promela message passing syntax in the MSC is an abstraction of `send` and `receive` Haskell function calls in the HdpH-RS implementation (Section 5.5.2). Node B is the victim, and node C is the thief. Node A hosts supervised future $i\{j\langle\langle M\rangle\rangle^{\S}_{B}\}_{A}$ (Section 3.4.3). Once the message sequence is complete, the new supervised future state is $i\{j\langle\langle M\rangle\rangle^{\S}_{C}\}_{A}$.

An example of recovering a supervised spark with the `recovery_supervised_spark` rule is shown in Figure 4.4. The supervised spark j of supervised future $i\{j\langle\langle M\rangle\rangle^{\S}_{C}\}_{A}$ is on node C. The node hosting i receives a `DEADNODE` message about node C, and creates a new replica k. The existence and location state of k is added to the supervised future $i\{k\langle\langle M\rangle\rangle^{\S}_{A}\}_{A}$.

Worker State

The local state of a worker is shown in Listing 4.9. When a thieving node proactively sends a fish to another node, the `waitingFishReplyFrom` stores the channel index identifier for the victim i.e. 0, 1 or 2 if targeting a worker node, or 3 if targeting the supervisor.

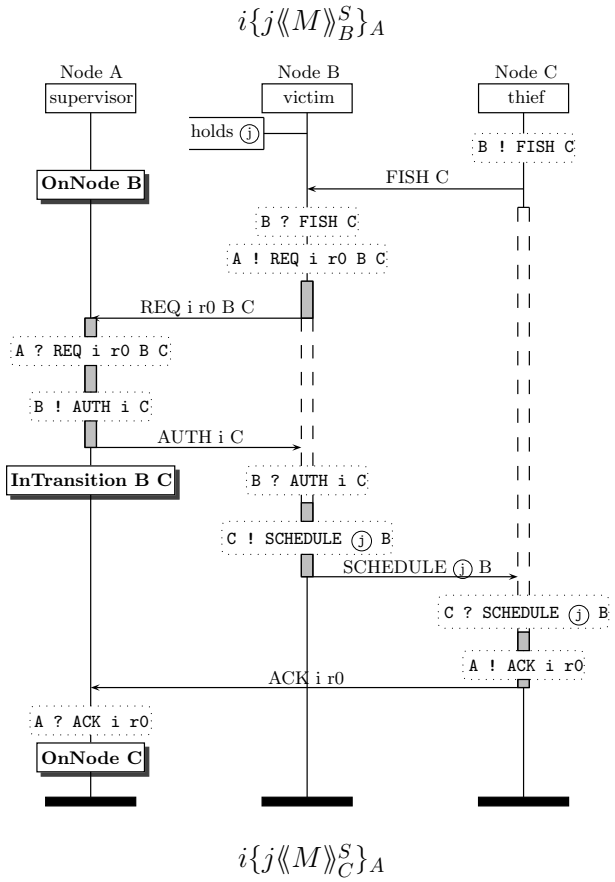


Figure 4.3: Location Tracking with `migrate_supervised_spark` Transition Rule

The value of `waitingFishReplyFrom` is reset to -1 when a `SCHEDULE` is received, or `NOWORK` message is received allowing the node to resume fishing. When a victim has sent a `REQ` to the supervisor, the `waitingSchedAuth` boolean on line 4 is used to reject subsequent fishing attempts from other thieves until it receives a `AUTH` or `NOWORK`. When a worker sends a `FISH`, it records the target in `lastTried` on line 7. If a `NOWORK` message is received, then this value is used to ensure that the new target is not the most recent target. This avoids cyclic states in the model when the same victim forever responds `FISH` requests with a `NOWORK` replies to the thief. Lastly, the `dead` boolean (line 6) is used to represent node failure in the model. Once this is switched to `true`, the `report_death` macro (Section 4.3.2) is used to transmit a `DEADNODE` message to all other nodes.

4.3.4 Spark Location Tracking

When the task tracker records on the supervisor is `ONNODE`, then it can be sure that the node identified with `spark.location.at` (line 13 of Listing 4.8) is holding the spark. If the node fails at this point, then the spark should be recreated as it has certainly been lost. However, when a spark is in transition between two nodes i.e `INTRANSITION`,

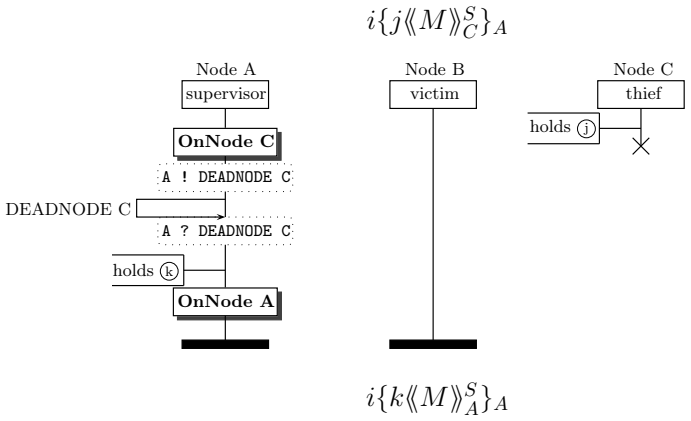


Figure 4.4: Supervised Spark Recovery with `recover_supervised_spark` Transition Rule

the supervisor cannot be sure of the location of the spark (Section 3.5.2); it is on either of the nodes identified by `spark.location.from` or `spark.location.to` (lines 11 and 12). To overcome this uncertainty, the model faithfully reflects the HdpH-RS pessimistic duplication strategy in algorithm 10 when a `DEADNODE` is received. This potentially generates replicas that concurrently exist in the model. This is handled using replica counts (Section 3.5.3).

4.3.5 Message Handling

This section presents the message handling in the Promela abstraction that models the fault tolerant scheduling algorithm from Section 3.5.4. An example control flow sequence on the supervisor is:

1. Receive a `REQ` from a victim targeted by a thief for supervised $spark_1$.
2. Check that the location for $spark_1$ is `ONNODE victim`.
3. Modify location status for $spark_1$ to `INTRANSITION victim thief`.
4. Send an `AUTH` to the victim.

Steps 2 and 3 are indivisibly atomic in the HdpH-RS design, as the message handler on each node is single threaded. That is, steps 2, 3 and 4 are executed by the message handler before the next message is received. Location state is implemented in HdpH-RS as a mutable `IORef` variable, and steps 2 and 3 check and modify the state of the `IORef` atomically using `atomicModifyIORef`. The message handling in the Promela model therefore follows the pattern of: receiving a message; atomically modify local state; and possibly ended with sending a message.

The Promela `atomic` primitive can be used for defining fragments of code to be executed indivisibly. There is also a `d_step` primitive that serves the same purpose, though with limitations. There can be no `goto` jumps, non-deterministic choice is executed deterministically, and code inside `d_step` blocks must be non-blocking. The Promela abstraction of HdpH-RS scheduling nevertheless opts for `d_step` blocks in favour of `atomic` blocks after receiving messages whenever possible. A `d_step` sequence can be executed much more efficiently during verification than an atomic sequence. The difference in performance can be significant, especially in large-scale verification [124].

FISH Messages

Fish messages are sent between worker nodes, from a thief to a victim. When a victim receives a fish request, it checks to see if it holds the spark, and if it is not waiting for authorisation from the supervisor node to schedule it elsewhere. If this is the case, the state of `waitingSchedAuth` for the spark is set to true, and a `REQ` is sent to the supervisor node. Otherwise, the thief is sent a `NOWORK` message. The reaction to receiving a `FISH` is shown in Listing 4.10, corresponding to Algorithm 2 of Section 3.5.4.

```
1  /* on worker nodes */
2  chans[me] ? FISH(thiefID, null, null) →
3      if   /* worker has spark and is not waiting for scheduling authorisation */
4        :: (worker[me].sparkpool.spark_count > 0 && ! worker[me].waitingSchedAuth) →
5           worker[me].waitingSchedAuth = true;
6           chans[3] ! REQ(me, thiefID, worker[me].sparkpool.spark);
7        :: else → chans[thiefID] ! NOWORK(me, null, null) ; /* worker doesn't have the spark */
8      fi
9
10 /* on the supervisor */
11 chans[3] ? FISH(thiefID, null,null) →
12     if   /* supervisor has spark and is not waiting for scheduling authorisation from itself */
13       :: (supervisor.sparkpool.spark_count > 0 && ! supervisor.waitingSchedAuth) →
14          supervisor.waitingSchedAuth = true;
15          chans[3] ! REQ(3, thiefID, supervisor.sparkpool.spark);
16       ::  else → chans[thiefID] ! NOWORK(3, null,null) ; /* supervisor don't have the spark */
17     fi;
```

Listing 4.10: Response to `FISH` Messages

REQ Messages

This message is sent from a victim to the supervising node. The first check that a supervisor performs is the comparison between the highest replication number of a task copy `spark.highestSequence` and the replication number of the task to be authorised for scheduling `seq`. If they are not equal, then an `OBSOLETE` message is sent to the victim, indicating that the task should be discarded. This checks that the spark to be stolen is the most recent copy of a future task in HdpH-RS.

If the replication numbers are equal, there is one more condition to satisfy for authorisation to be granted. The supervising node only authorises the migration of the spark if the book keeping status of the spark is `ONNODE` (see Section 3.5.2). If this is the case, the spark book keeping is set to `INTRANSITION`, updating the `spark.location.from` and `spark.location.to` fields to reflect the movement of the spark. Finally, the `AUTH` message is sent to the victim. If the context of the spark is `INTRANSITION`, the schedule request from the victim is denied by responding with `DENIED`. The reaction to receiving a `REQ` is shown in Listing 4.11, corresponding to Algorithm 3 of Section 3.5.4.

```
1  chans[3] ? REQ(victimID, thiefID, seq) →
2      if
3        :: seq == spark.highestSequence →
4           if
5                /* conditions for authorisation */
6             :: spark.context == ONNODE && ! worker[thiefID].dead→
7                d_step {
8                  spark.context  = INTRANSITION;
9                  spark.location.from = victimID ;
10                 spark.location.to = thiefID ;
11               }
12               chans[victimID] ! AUTH(thiefID, seq, null); /* authorise request */
13
14               /* otherwise deny request */
15            :: else →
16               chans[victimID] ! DENIED(thiefID, seq, null); /* deny request */
17          fi
18       :: else →
19          chans[victimID] ! OBSOLETE(thiefID, null, null); /* obsolete sequence number */
20     fi
```

Listing 4.11: Response to `REQ` Messages

AUTH Messages

This message is sent from the supervising node to a victim that had requested authorisation to schedule the spark to a thief. There are no pre-conditions for the response — the victim sends the spark in a `SCHEDULE` message to the thief. The reaction to receiving an `AUTH` is shown in Listing 4.12, corresponding to Algorithm 4 of Section 3.5.4.

SCHEDULE Messages

A thief sends a victim a `FISH` message in the hunt for sparks. The victim will later reply with a `SCHEDULE` message, if authorised by the supervisor. The thief accepts the spark, and sends an `ACK` message to the supervisor of that spark. The reaction to receiving a `SCHEDULE` is shown in Listing 4.13, corresponding to Algorithm 6 of Section 3.5.4.

```
/* on worker nodes */
chans[me] ? AUTH(thiefID, authorisedSeq, null) →
    d_step {
      worker[me].waitingSchedAuth = false;
      worker[me].sparkpool.spark_count--;
      worker[me].waitingFishReplyFrom = -1;
    }
    chans[thiefID] ! SCHEDULE(me, worker[me].sparkpool.spark, null);

/* on the supervisor */
chans[3] ? AUTH(thiefID, authorizedSeq, null) →
    d_step {
      supervisor.waitingSchedAuth = false;
      supervisor.sparkpool.spark_count--;
    }
    chans[thiefID] ! SCHEDULE(3, supervisor.sparkpool.spark ,null);
```

Listing 4.12: Response to AUTH Messages

```
chans[me] ? SCHEDULE(victimID, seq, null) →
    d_step {
      worker[me].sparkpool.spark_count++;
      worker[me].sparkpool.spark = seq ;
      spark.age++;
    }
    chans[3] ! ACK(me, seq, null) ; /* Send ACK To supervisor */
```

Listing 4.13: Response to SCHEDULE Messages

ACK Messages

This message is sent from a thief to the supervisor. An ACK is only acted upon if the replication number seq for the task equals the replication number known by the supervisor. If they are not equal, the ACK is simply ignored. If the replication numbers are equal, the response is an update of the location state for that spark — switching from INTRANSITION to ONNODE. The reaction to receiving a ACK is shown in Listing 4.14, corresponding to Algorithm 7 of Section 3.5.4.

```
chans[3] ? ACK(thiefID, seq, null) →
    if   /* newest replica arrived at thief */
      :: seq == spark.highestSequence →
         d_step {
           spark.context = ONNODE;
           spark.location.at = thiefID ;
         }

         /* ACK not about newest replica */
      :: else → skip ;
    fi
```

Listing 4.14: Response to ACK Messages

DENIED Messages

This message is sent from the supervising node to a victim that had requested authorisation to schedule the spark to a thief. There are no pre-conditions for the response — the victim sends a `NOWORK` message to the thief. The reaction to receiving an `DENIED` is shown in Listing 4.15, corresponding to Algorithm 8 of Section 3.5.4.

```
1  /* on worker nodes */
2  chans[me] ? DENIED(thiefID, deniedSeq, null) →
3      worker[me].waitingSchedAuth = false;
4      chans[thiefID] ! NOWORK(me, null, null) ;
5
6  /* on the supervisor */
7  chans[3] ? DENIED(thiefID, deniedSeq,null) →
8      supervisor.waitingSchedAuth = false;
9      chans[thiefID] ! NOWORK(3, null, null) ;
```

Listing 4.15: Response to `DENIED` Messages

NOWORK Messages

A thief may receive a `NOWORK` in response to a `FISH` message that it had sent to a victim. This message was returned either because the victim did not hold the spark, or because the victim was waiting for authorisation to schedule the spark in response to an earlier `FISH` message. When a `NOWORK` message is received, the thief is free to target another victim for work. The reaction to receiving a `NOWORK` is shown in Listing 4.16, corresponding to Algorithm 9 of Section 3.5.4.

```
1  chans[me] ? NOWORK(victimID, null, null) →
2      worker[me].waitingFishReplyFrom = -1;  /* can fish again */
```

Listing 4.16: Response to `NOWORK` Messages

OBSOLETE Messages

An `OBSOLETE` message is sent from a supervisor to a victim. It is a possible response message to a `REQ` message when a scheduling request is made with respect to an old spark copy. The message is used to inform a victim to discard the spark, which then returns a `NOWORK` message to the thief. The reaction to receiving an `OBSOLETE` is shown in Listing 4.17, corresponding to Algorithm 5 of Section 3.5.4.

```
1  chans[me] ? OBSOLETE(thiefID, null, null) →
2      d_step {
3        worker[me].waitingSchedAuth = false;
4        worker[me].sparkpool.spark_count--;
5        worker[me].waitingFishReplyFrom = -1;
6      }
7      chans[thiefID] ! NOWORK(me, null, null) ;
```

Listing 4.17: Response to `OBSOLETE` Messages

DEADNODE Messages

The HdpH-RS transport layer propagates `DEADNODE` messages to a node that has lost a connection with another node. This message has a purpose for both the supervisor of the spark, and worker nodes who may be waiting for a fishing reply from the failed node. The reaction to receiving a `DEADNODE` is shown in Listing 4.18, corresponding to Algorithm 10 of Section 3.5.4.

Worker If a thief node has previously sent a `FISH` message to a victim node, it will be involved in no scheduling activity until receiving a reply. If the victim fails, it will never return a reply. So instead, the `DEADNODE` message is used to unblock the thief, allowing to fish elsewhere.

Supervisor If the supervising node receives indication of a failed worker node, then it must check to see if this affects the liveness of the spark. The location status of the spark is checked. If the spark was on the failed node at the time of the failure, the supervisor recreates the spark in its local sparkpool from line 27. Furthermore, if the spark was in transition towards or away from the failed node, again the spark is recreated on the supervisor locally. An example of this is in Figure 4.4 in Section 4.3.3. A migration of supervised spark j is attempted with the `migrate_supervised_spark` rule, from B to C. Node C fails. The liveness of supervised spark j cannot be determined, so the `recover_supervised_spark` is triggered to create a replica k on node A. This is affected in the Promela model in Listing 4.18.

Node Automata

The `Supervisor` and `Worker` nodes are both translated in to a finite automaton. SPIN is used in Section 4.5 to search the intersection of `Supervisor`, `Worker` and `Scheduler` with the LTL property automaton in Section 4.4.1 to validate the HdpH-RS scheduler abstraction. The finite automaton for the `Supervisor` node is shown in Figure 4.5. The finite automaton for the `Worker` node is shown in Figure 4.6.

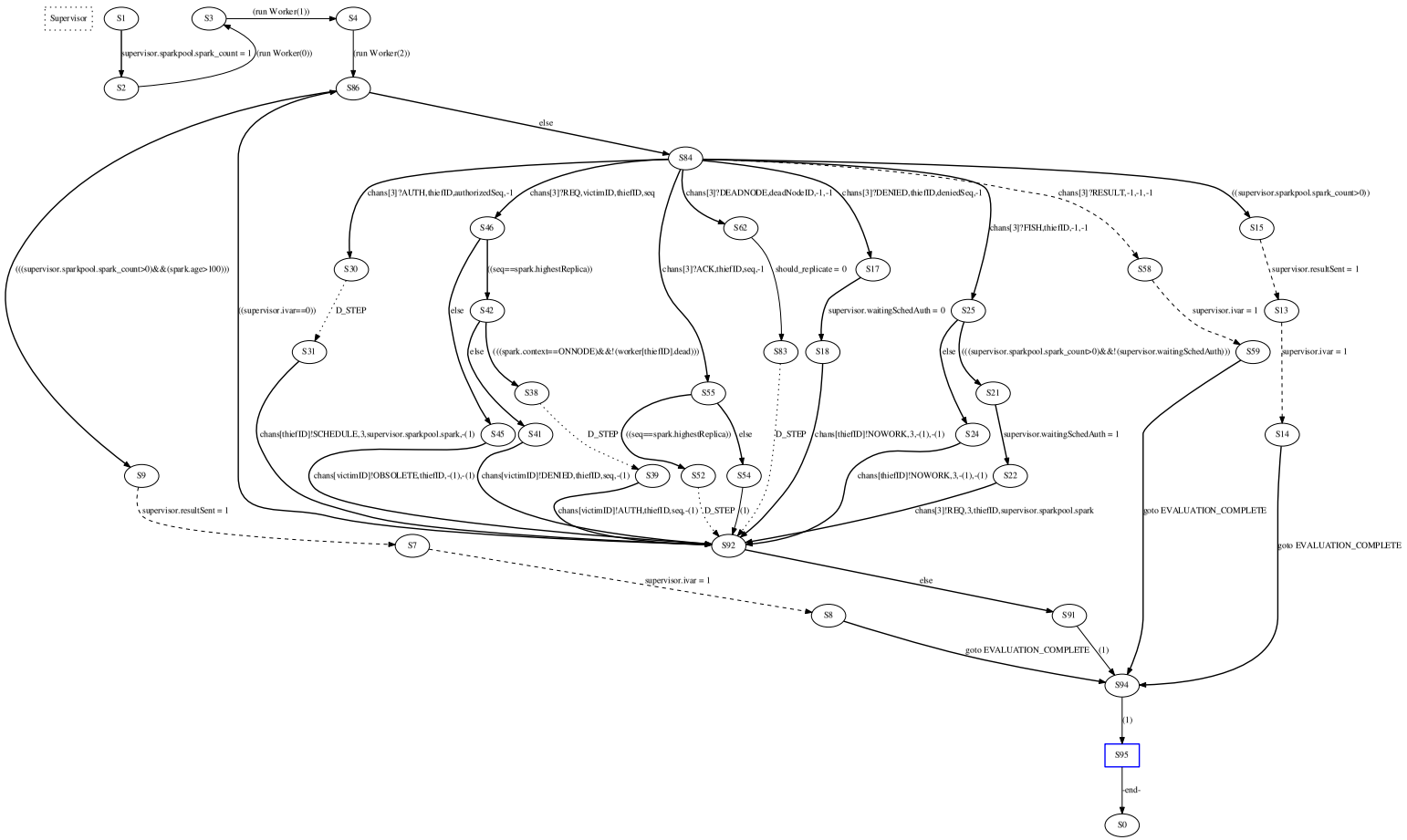


Figure 4.5: Supervisor Automata

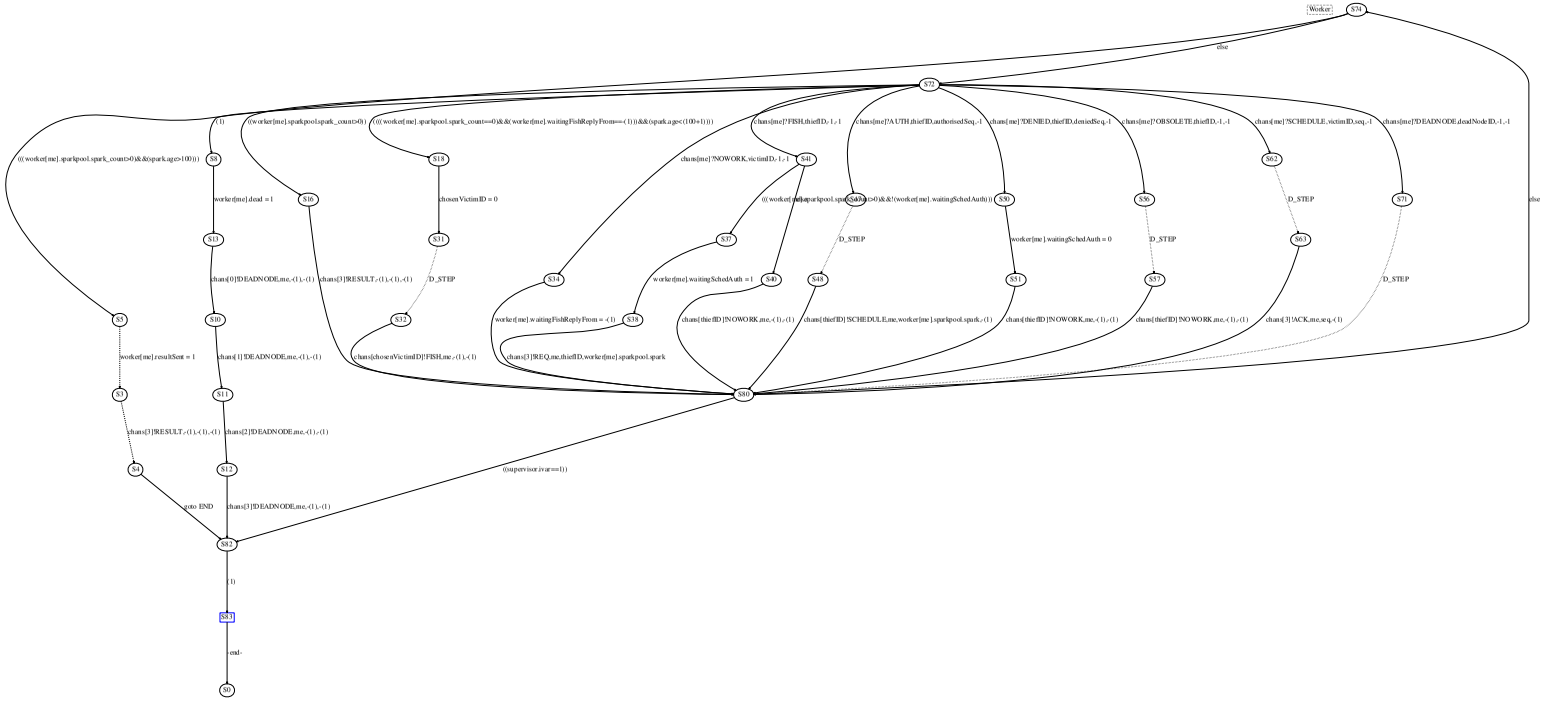


Figure 4.6: Worker Automata

```
/* On a worker node */
chans[me] ? DEADNODE(deadNodeID, null, null) →
    d_step {
      if   /* reset to start fishing from other nodes */
        :: worker[me].waitingFishReplyFrom > deadNodeID →
           worker[me].waitingFishReplyFrom = -1 ;
        :: else → skip ;
      fi
    }

/* On the supervising node */
chans[3] ? DEADNODE(deadNodeID, null, null) →
    bool should_replicate;
    d_step {
      should_replicate = false;

      if   /* decide if spark needs replicating */
        :: spark.context == ONNODE \
           && spark.location.at == deadNodeID → should_replicate = true;
        :: spark.context  == INTRANSITION \
           && (spark.location.from == deadNodeID \
               || spark.location.to == deadNodeID) → should_replicate = true;
        :: else → skip;
      fi;

      if   /* replicate spark */
        :: should_replicate →
           spark.age++;
           supervisor.sparkpool.spark_count++;
           spark.highestSequence++;
           supervisor.sparkpool.spark = spark.highestSequence ;
           spark.context = ONNODE;
           spark.location.at = 3 ;
        :: else → skip;
      fi;
    }
```

Listing 4.18: Response to `DEADNODE` Messages

4.4 Verifying Scheduling Properties

SPIN is used to generate an optimised verification program from the high level specification. If any counterexamples to the Linear Temporal Logic (LTL) correctness claims are detected, these can be fed back into the interactive simulator and inspected in detail to establish and remove their cause. Section 4.4.1 presents the LTL grammar and propositional symbols used in the key resiliency properties in Section 4.5.

4.4.1 Linear Temporal Logic & Propositional Symbols

Temporal logic [134] provides a formalism for describing the occurrence of event in time that is suitable for reasoning about concurrent programs [130]. To prove that a program satisfies some property, a standard method is to use LTL model checking. When the property is expressed with an LTL formula, the SPIN model checker transforms the negation of this formula into a Büchi automaton, building the product of that automaton

$\langle \phi \rangle$ ::= `p`
| `true`
| `false`
| (ϕ)
| $\langle \psi \rangle$ $\langle binop \rangle$ $\langle \phi \rangle$
| $\langle \psi \rangle$ $\langle unop \rangle$ $\langle \phi \rangle$

$\langle unop \rangle$ ::= $\Box$ (always)
| $\Diamond$ (eventually)
| `!` (logical negation)

$\langle binop \rangle$ ::= $\mathcal{U}$ (strong until)
| `&&` (logical and)
| `||` (logical or)
| $\rightarrow$ (implication)
| $\leftrightarrow$ (equivalence)

Figure 4.7: LTL Grammar

Formula	Explanation
$\Box\phi$	ϕ must always hold
$\Diamond\Box\phi$	ϕ must eventually always hold
$\psi\,\mathcal{U}\,\phi$	ψ must hold until at least ϕ is true

Table 4.1: LTL Formulae Used To Verify Fault Tolerant Scheduler

with the programs, and checks this product for emptiness [67]. An LTL formula ϕ for SPIN may contain any propositional symbol p, combined with unary or binary, boolean and/or temporal operators [83], using the grammar in Figure 4.7. LTL is used to reason about causal and temporal relations of the HdpH-RS scheduler properties. The special temporal operators used for verifying the fault tolerant scheduling design in Section 4.5 are shown in Table 4.1.

SPIN translates LTL formulae into `never` claims, automatically placing accept labels within the claim. The SPIN verifier then checks to see if this `never` claim can be violated. To prove that no execution sequence of the system matches the negated correctness claim, it suffices to prove the absence of acceptance cycles in the combined execution of the system and the Büchi automaton representing the claim [83]. An LTL formula is a composition of propositional symbols, which are defined with macros, .e.g. `#define p (x > 0)`. The propositional symbols used in the verification of scheduling Promela model are shown in Listing 4.19.

4.4.2 Verification Options & Model Checking Platform

Verification Options

Listing 4.20 shows how the SPIN verifier is generated, compiled and executed.

Generation The `-a` flag tells SPIN to generate a verifier in a `pan.c` source file. The `-m`

```
1  /* IVar on the supervisor node is full */
2  #define ivar_full  ( supervisor.ivar == 1 )
3
4  /* IVar on the supervisor node is empty */
5  #define ivar_empty ( supervisor.ivar == 0 )
6
7  /* No worker nodes have failed */
8  #define all_workers_alive ( !worker[0].dead && !worker[1].dead && !worker[2].dead )
9
10 /* One or more nodes have transmitted a value to supervisor to fill IVar */
11 #define any_result_sent ( supervisor.resultSent
12                           || worker[0].resultSent
13                           || worker[1].resultSent
14                           || worker[2].resultSent )
```

Listing 4.19: Propositional Symbols used in LTL Formulae of Fault Tolerant Properties

```
1 $ spin -a -m hdph-rs.pml
2 $ gcc -DMEMLIM=1024 -O2 -DXUSAFE -DCOLLAPSE -w -o pan pan.c
3 $ ./pan -m10000  -E -a -f -c1 -N never_2
```

Listing 4.20: Compiling & Executing SPIN Verifier

flag tells SPIN to lose messages sent to full channel buffers. This reflects the impossibility of filling a TCP receive buffer on a dead HdpH-RS node. The `-m` flag prevents healthy nodes from blocking of full channels in the model.

Compilation The memory limit is set to 1024Mb with the `-DMEMLIM` flag. Checks for channel assertion violations are disabled with `-DXUSAFE`, as they are not used. The `-DCOLLAPSE` flag enables state vector compression.

Verification The maximum search space is set to 10000 with the `-m` flag, and a maximum of 124 is used. The `-a` flag tells SPIN to check for acceptance cycles in the LTL property automata. Weak fairness is enabled with the `-f` flag. The `-E` flag suppresses the reporting of invalid end states. This ensures that every statement always enabled from a certain point is eventually executed. The verification ends after finding the first error with the `-c` flag. The `-N` flag selects the LTL property to be verified.

4.5 Model Checking Results

This section reports the results of SPIN verification. The results of model checking the three LTL properties are in Table 4.2. Taking the $\Diamond \Box \, ivar\_full$ property as an example, the results can be interpreted as follows. A reachable depth of 124 is found by SPIN for the model. The reachable state space is 8.2 million. A total of 22.4 million transitions were explored in the search. Actual memory usage for states was 84.7Mb.

LTL Formula	Errors	Depth	States	Transitions	Memory
$\Box$ *all_workers_alive*	Yes	11	5	5	0.2Mb
$\Box$ (*ivar_empty* $\mathcal{U}$ *any_result_sent*)	No	124	3.7m	7.4m	83.8Mb
$\Diamond \Box$ *ivar_full*	No	124	8.2m	22.4m	84.7Mb

Table 4.2: Model Checking Results

4.5.1 Counter Property

Validating the Possibility of Worker Node(s) Fail

To check that worker nodes are able to fail in the model, a verification attempt is made on the $\Box$ *all_workers_alive* LTL formula. To check that the model has the potential to kill mortal workers, SPIN searches for a counter-example system state with any of the `worker[0].dead`, `worker[1].dead` or `worker[2].dead` fields set to `true`. SPIN trivially identifies a counter example after searching 5 system states by executing the choice on line 15 in Listing 4.4 to kill a node.

4.5.2 Desirable Properties

The IVar is Empty Until a Result is Sent

To check that the model is faithful to the fact that an `IVar` is empty at least until its corresponding task has been evaluated, the $\Box$ (*ivar_empty* $\mathcal{U}$ *any_result_sent*) formula is verified. SPIN searches for two violating system states. First, where `any_result_sent` is true when `ivar_empty` is false. Second, a cycle of identical system states is identified while `any_result_sent` remains false. This is due to the nature of the *strong until* connective stipulating that `any_result_sent` must eventually be true in some future state. This is preferred to the *weak until* connective, which would not verify that a result is ever sent to the supervisor. SPIN cannot find a violating system state after exhaustively searching 3.7 million reachable states up to a depth of 124.

The IVar is Eventually Always Full

The key property for fault tolerance is that the `IVar` on the supervisor must eventually always be full. This would indicate that either a worker node has sent a `RESULT` message, or the supervisor has written to the `IVar` locally. The $\Diamond \Box$ *ivar_full* formula is verified. SPIN searches for a system state cycle when `ivar_full` remains false i.e. `supervisor.ivar==0`. Each time the spark is passed to a node, its age is incremented. Each time the supervisor creates a replica, the spark's age is incremented. When this age reaches 100, the model enforces the deterministic choice of sending a `RESULT` message to

the supervisor on any nodes that hold a replica, representing `rput` calls in HdpH-RS. The supervisor sets `supervisor.ivar` to 1 when it receives a `RESULT` message.

This LTL property checks for the fatal scenario when the supervisor does not replicate the spark in the model, when it must in order to ensure the existence of at least one replica. This would happen if the HdpH-RS fault tolerant fishing protocol algorithm (Section 3.5.4) did not catch corner cases whereby spark location tracking becomes invalidated. The consequence would be the supervisor's incorrect decision not to replication the spark when a `DEADNODE` message is received. Should the location tracking be invalidated and the dead node held the only replica, no nodes would ever be able to send a `RESULT` message to the supervisor. SPIN therefore searches for states where the `spark_count` value is 0 for all nodes, and the supervisor does not create a replica in any future state. SPIN cannot find a violating system state after exhaustively searching 8.2 million reachable states up to a depth of 124.

4.6 Identifying Scheduling Bugs

SPIN identified bugs in the fault tolerant scheduling algorithm (Section 3.5.4), which were abstracted into earlier iterations of the Promela model. This section describes one of many examples of how SPIN identified transitions to violating states with respect to the $\Diamond \Box \, ivar\_full$ property. Each bug was removed with modifications to the scheduling algorithm (Section 3.5.4), and corresponding fixes in the Haskell scheduler implementation (Chapter 5). With respect to the bug described here, the fix to the Promela model and the Haskell implementation is shown in Appendix A.4.

The Bug

The LTL formula `<> [] ivar_full` claims that the empty `IVar` is eventually always full. Attempting to verify this property uncovered a corner case that would lead to deadlock and an `IVar` would never been filled with a value. There were insufficient pre-conditions for sending an `AUTH` message from a supervisor, in an earlier version of the model. The counter example that SPIN generated is shown in Figure 4.8. The supervisor node A will not receive another `DEADNODE` message about node C after sending the `AUTH` message, so the supervised spark would not be recovered and the `IVar` will never by filled.

The Fix

The fix was to add an additional guard on the supervisor, before sending an `AUTH` to the victim (line 6 of Listing 4.11). Each `REQ` message includes a parameter stating who the

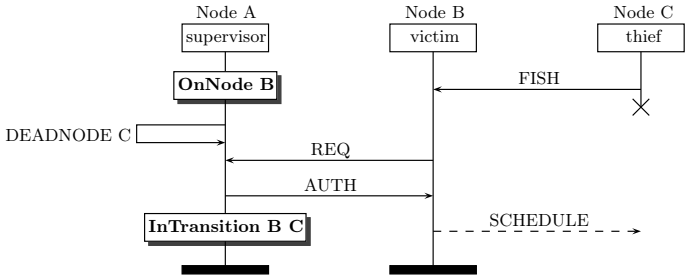


Figure 4.8: Identified Bug Of Scheduling Algorithm Using Promela Model

thief is (Section 3.5.1). When a `DEADNODE` message is received, the HdpH-RS scheduler removes the failed node from its local virtual machine (VM). The fix ensures that the thief specified in a `REQ` message is in the supervisor's VM.

Chapter 5

Implementing a Fault Tolerant Programming Language and Reliable Scheduler

This chapter presents the implementation of the HdpH-RS fault tolerant primitives and verified reliable scheduler. The implementation of the HdpH-RS system architecture is described in Section 5.1. The `supervisedSpawn` and `supervisedSpawnAt` implementations are described in Section 5.2. Task recovery implementation is described in Section 5.3. The state each node maintains is described in Section 5.4. The HdpH-RS transport layer and distributed virtual machine implementations are described in Section 5.5. This includes a discussion on detecting failures at scale. The failure detection in HdpH-RS periodically checks for lost connections rather than assuming failure with timeouts, which may produce false positives when latency's are variable and high.

A comparison with four fault tolerant programming model implementations is made in Section 5.6. They are fault tolerant MPI, Erlang, Hadoop MapReduce, and the fault tolerance designs for Glasgow distributed Haskell.

5.1 HdpH-RS Architecture

The HdpH-RS architecture is closely based on the HdpH architecture [114]. The architecture supports semi-explicit parallelism with work stealing, message passing and the remote writing to `IVar`s. The HdpH-RS architecture shown in Figure 5.1 extends the HdpH architecture presented in Section 2.6 in 5 ways.

1. **IVar Representation** The representation of `IVar`s has been extended from HdpH to support the fault tolerant concept of *supervised futures* (Section 3.3.2). A super-

vised empty future (`IVar`) in HdpH-RS stores the location of its corresponding supervised spark or thread, replication counters and a scheduling policy *within* the `IVar` (Section 5.1.1).

2. **Reliable Scheduling** The work stealing scheduler from HdpH is extended for fault tolerance, an implementation of the design from Section 3.5.

3. **Failure Detection** The message passing module in HdpH-RS uses a fault detecting TCP-based transport layer (Section 5.5.4).

4. **Guard post** Each node has an additional piece of state, a *guard post*, with a capacity to hold one spark. It is used to temporarily suspend a spark that is awaiting authorisation to migrate to a thief. The purpose of guard posts has previously been described in Section 3.5.2. The implementation is shown in Section 5.1.2.

5. **Registry** The registry on each HdpH-RS node stores globalised `IVar`s. It is used to identify at-risk computations upon failure detection, by inspecting internal state of empty `IVar`s for corresponding supervised spark or supervised thread locations.

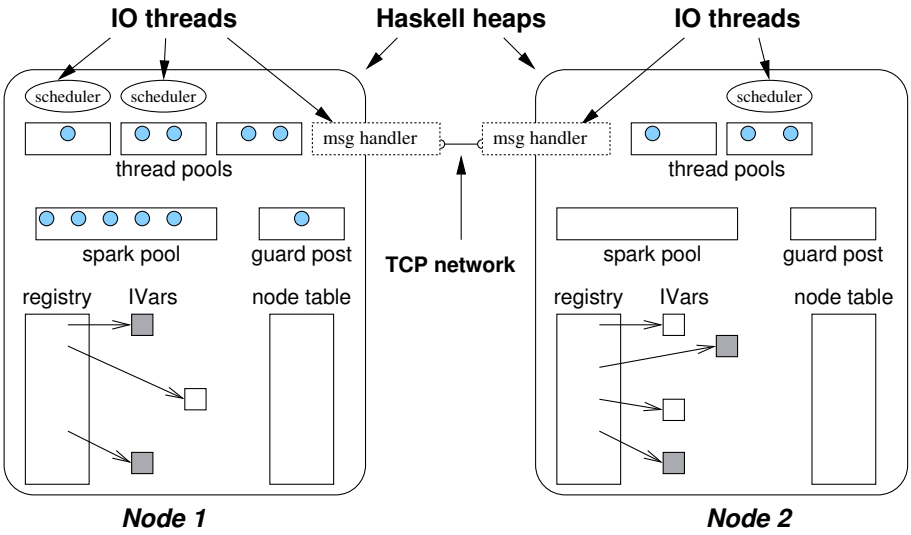


Figure 5.1: HdpH-RS System Architecture

The HdpH code is a collection of hierarchical Haskell modules, separating the functionality for threadpools, sparkpools, communication and the exposed programming API. The module hierarchy is given in Figure 5.2 showing its association with the transport layer, and illustrates how a user application uses the HdpH-RS API.

In extending HdpH, the `FTStrategies` module is added for the fault tolerant strategies (Section 6.1), and 14 modules are modified. This amounts to an additional 1271 lines of Haskell code in HdpH-RS, an increase of 52%. The increase is mostly attributed to the

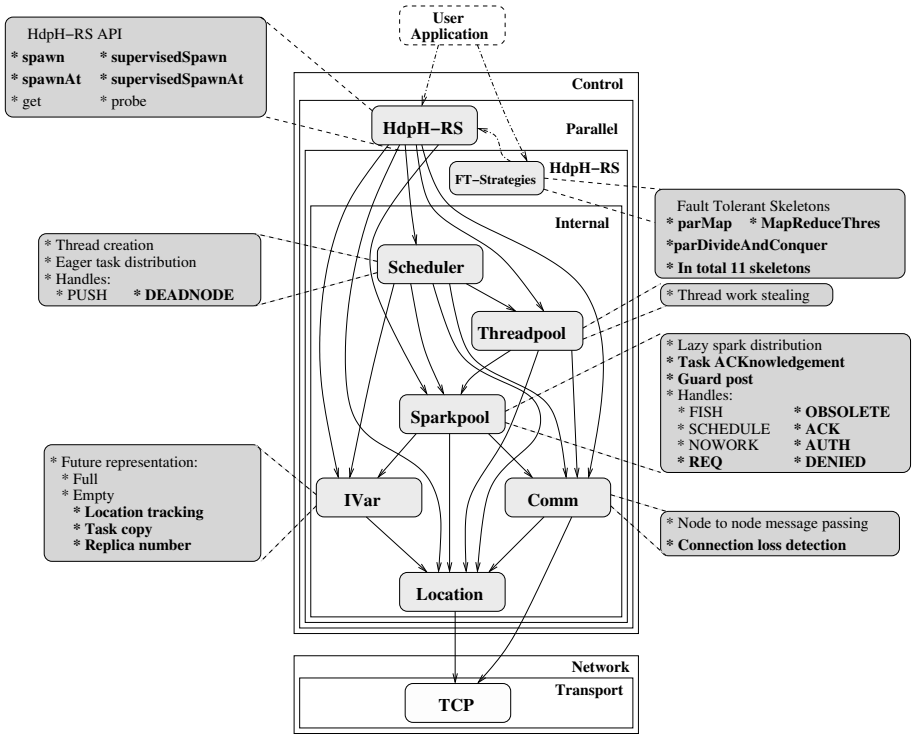


Figure 5.2: HdpH-RS Module View (extensions from HdpH modules in **bold**)

new spawn family of primitives, fault detection and recovery, and task supervision code in the `Scheduler`, `Sparkpool`, `IVar` and `Comm` modules.

5.1.1 Implementing Futures

A case study of programming with futures is given in Appendix A.2, and the use of `IVar`s as futures in HdpH-RS is described in Section 3.3.2. The implementation of futures in HdpH-RS is shown in Listing 5.1. The state of a future is stored in `IVarContent` on line 2. An `IVar` is implemented as a mutable `IVarContent`, in an IORef on line 1. The `IVarContent` data structure supports both supervised and unsupervised futures. An empty future created with `spawn` or `spawnAt` is implemented as `Empty [] Nothing`. A supervised empty future, created with `supervisedSpawn` or `supervisedSpawnAt`, is implemented as `Empty [] (Just SupervisedFutureState)`. The task tracking, replica count and back-up copy of the task expression are stored in `SupervisedFutureState`, and is described shortly. It is necessary for recovering lost supervised sparks and threads.

In both supervised and unsupervised futures, the definition of a full future is the same. A `Full a` value on line 3 represents a full `IVar` $i\{M\}_n$, where i on node n holds the value M. When an `rput` writes to an `IVar`, its state changes from `Empty _ _` to `Full a`. All blocked threads are woken up and informed of the value in the `IVar`. All information about its previously empty state can now be garbage collected. Once the `IVar` is full, the

```
1  type IVar a = IORef (IVarContent a)
2  data IVarContent a =
3        Full a
4      | Empty
5    { blockedThreads :: [a → Thread]
6    , taskLocalState :: Maybe SupervisedFutureState }
```

Listing 5.1: `IVar` Representation in HdpH-RS

	Supervision State		Future State
	On supervisor	Within Spark/Thread	
`spawn`	✗	✗	$i\{\}_n$
`spawnAt`	✗	✗	$i\{\}_n$
`supervisedSpawn`	`SupervisedFutureState`	`SupervisedSpark`	$i\{j\langle\langle M\rangle\rangle^{S}_{n'}\}_n$
`supervisedSpawnAt`	`SupervisedFutureState`	✗	$i\{j\langle M\rangle_{n'}\}_n$

Table 5.1: Supervision State

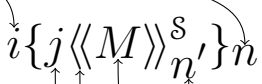
HdpH-RS scheduler has satisfied the resiliency property that the `IVar` will be eventually filled despite the presence of remote node failure (Section 4.5).

There are 2 pieces of supervision state. The first is within an `IVar`, and stored locally in a `SupervisedFuturesState` structure. The atomic states in the operational semantics in Section 3.4 show that of all task states, only supervised sparks need additional state recording a supervised spark's location and its replica number. Threads that correspond to supervised threaded futures do not travel with supervision state, as they cannot migrate after being pushed to the target node. Supervised futures and supervised spark state is summarised in Table 5.1. The supervision state within a supervised spark is later presented as `SupervisedSpark` in Listing 5.5.

Supervised Empty Future State

The `SupervisedFutureState` data structure in Figure 5.3 is used to implement supervised futures and is stored in the registry, one entry per supervised future. A copy of the corresponding task expression is stored within the empty future as `task` on line 13. When a remote node failure puts the liveness of the corresponding task in jeopardy, `task` is extracted from the empty `IVar` and rescheduled as a replica. The replication number `replica` on line 8 in the registry is incremented. The j value in a supervised future $i\{j\langle\langle M\rangle\rangle^{S}_{n'}\}_n$ is implemented as a replica number, and ensures that obsolete spark copies are no longer permitted to migrate in accordance with `migrate_supervised_spark` rule in Section 3.4.3. The `scheduling` field on line 11 captures whether the future task was created as a spark with `supervisedSpawn` or as a thread with `supervisedSpawnAt`, using

```
1  -- supervised sparked future is a globalised IVar: (Empty [] (Just SupervisedFutureState))
2  type GIVar a = GRef (IVar a)
3  data GRef a = GRef { slot :: !Integer, at:: !NodeId }
```



```
4  -- | Supervision state in IVar
5  data SupervisedFutureState =
6    SupervisedFutureState
7     { -- | highest replica number.
8       replica :: Int
9       -- | Used when rescheduling
10      -- recovered tasks.
11    , scheduling :: Scheduling
12      -- | The copy of the task expression.
13    , task :: Closure (Par ())
14      -- | location of most recent task copy.
15    , location :: CurrentLocation }
16
17 -- | spark location.
18 data CurrentLocation =
19   OnNode NodeId | InTransition { movingFrom :: NodeId , movingTo :: NodeId }
20
21 -- | The task was originally created as a spark
22 --  or as an eagerly scheduled thread.
23 data Scheduling = Sparked | Pushed
```

Figure 5.3: Implementation of State for Supervised Sparked Futures

the definition `Scheduling` on line 23. This is used in the recovery of the future task, determining whether it goes into a local threadpool or the local sparkpool, in accordance with Algorithm 10 in Section 3.5.4. To determine the safety of a task in the presence of failure, its location is stored within the empty `IVar` on line 15. The `CurrentLocation` definition is on line 18. A supervised spark created with `supervisedSpawn` is either `OnNode thief` or `InTransition victim thief`. A thread created with `supervisedSpawnAt` is immediately updated to `OnNode target`.

The definition of task references and 4 location tracking functions on `IVar`s are shown in Listing 5.2. Task references of type `TaskRef` on line 2 are used by the scheduler to inspect location information of a spark to respond to `REQ` messages, and modify the location tracking state in response to `AUTH` and `ACK` messages (Section 3.5.1). The `locationOfTask` on line 6 is used to lookup whether the corresponding supervised spark is `OnNode` or `InTransition`, to determine a response to `REQ` (Algorithm 3 in Section

```
1  -- | wrapper for 'GRef a' from Figure 5.3, uniquely identifying an IVar.
2  data TaskRef = TaskRef { slotT :: !Integer, atT :: !NodeId }
3
4  -- | query location of task in response to REQ message.
5  --   return 'Just CurrentLocation' if IVar is empty, else 'Nothing'.
6  locationOfTask :: TaskRef → IO (Maybe CurrentLocation)
7
8  -- | set task to be InTransition before sending an AUTH message to a victim.
9  taskInTransition :: TaskRef → NodeId → NodeId → IO ()
10
11 -- | set task to be OnNode when ACK received by thief.
12 taskOnNode       :: TaskRef → NodeId → IO ()
13
14 -- | scans through local registry, identifying all at-risk IVars.
15 --   that is: all IVars whose corresponding spark or thread may be
16 --   been lost with the failure of the specified node.
17 vulnerableEmptyFutures :: NodeId → IO [IVar a]
```

Listing 5.2: Modifying Empty IVar Location

3.5.4). If the corresponding task for a supervised future is a thread, its location will always be `OnNode`, as threads cannot migrate. If the location state for a supervised spark is `OnNode`, then `taskInTransition` on line 9 is used to modify the location state, before an `AUTH` message is sent to the victim. If the location state for a supervised spark is `InTransition`, a `DENIED` message is sent to the victim, and the location state in the `IVar` is not modified. When an `ACK` is received from a thief, the location state for the remote spark is modified within the `IVar` with the `taskOnNode` function on line 12. Lastly, the `vulnerableEmptyFutures` on line 17 is used when a node receives a `DEADNODE` message propagated from the fault detecting transport layer.

```
1  -- | Par computation that generates registry entries in Table 5.2
2  foo :: Int → Par Integer
3  foo x = do
4      ivar1 ← supervisedSpawn   $(mkClosure [| f x |])
5      ivar2 ← supervisedSpawnAt $(mkClosure [| g x |]) nodeD
6      ivar3 ← spawn             $(mkClosure [| h x |])
7      ivar4 ← supervisedSpawn   $(mkClosure [| k x |])
8      ivar5 ← supervisedSpawn   $(mkClosure [| m x |])
9      ivar6 ← spawnAt           $(mkClosure [| p x |]) nodeF
10     ivar7 ← supervisedSpawn   $(mkClosure [| q x |])
11     ivar8 ← supervisedSpawn   $(mkClosure [| r x |])
12     ivar9 ← spawnAt           $(mkClosure [| s x |]) nodeB
13     x ← get ivar1
14     y ← get ivar2
15     {- omitted -}
```

Listing 5.3: Par Computation That Modifies Local Registry on Node A

Function Call	TaskRef		SupervisedFutureState				Vulnerable
	at	slot	task	scheduling	replica	location	
supervisedSpawn $(f\,x)$	A	1	$f\,x$	`Sparked`	2	`OnNode B`	No
supervisedSpawnAt $(g\,x)\,D$	A	2	$g\,x$	`Pushed`	1	`OnNode D`	Yes
spawn $(h\,x)$	A	3	`Nothing`				?
supervisedSpawn $(k\,x)$	A	4	$k\,x$	`Sparked`	3	`InTransition D C`	Yes
supervisedSpawn $(m\,x)$	A	5	$m\,x$	`Sparked`	1	`InTransition G F`	No
spawnAt $(p\,x)\,F$	A	6	`Nothing`				?
supervisedSpawn $(q\,x)$	A	7	`Full 394`				No
supervisedSpawn $(r\,x)$	A	8	$r\,x$	`Sparked`	1	`OnNode A`	No
spawnAt $(s\,x)\,B$	A	9	`Full 68`				No

Table 5.2: Using Registry on Node A To Recover Tasks When Failure of Node D Detected

An example of a local registry snapshot state is in Table 5.2. There have been 9 function calls on node A, as shown in Listing 5.3. Of these, six are calls to the fault tolerant primitives. The 3rd is a non-fault tolerant `spawn` call, and the 6th and 9th are non-fault tolerant `spawnAt` calls. When the failure of node D is detected, the registry is used to identify vulnerable remote tasks. In this case, tasks for futures `A:2` and `A:4` need recovering. Supervised futures `A:1`, `A:5` and `A:8` are not affected as their corresponding task is not at node D, or in transition to or from node D. Futures `A:7` and `A:9` are not affected because they are already full with values 394 and 68 respectively.

The safety of tasks for futures `A:3` and `A:6` cannot be determined, due to the use of non-fault tolerant primitives. The HdpH-RS RTS may deadlock if two conditions are met. First, that either of the tasks corresponding to futures `A:3` or `A:6` are lost with the loss of node D. Second, that the values of futures `A:3` or `A:6` are needed by the program i.e. are waited for with a blocking `get` operation. The MPI philosophy would be to terminate the entire program if the safety of all registered futures cannot be guaranteed. The HdpH-RS RTS does not take such brutal action in the case of this uncertainty, which raises the possibility of deadlock. One advantage of using the fault tolerant algorithmic skeletons in Section 6.1.2 is that accidental use of `spawn` or `spawnAt` is not possible when fault tolerant execution is the intention.

Supervised Spark State

The definition of a task is shown in Listing 5.4. Only sparks created with `supervisedSpawn` are defined as `Left (Closure (SupervisedSpark))`. Tasks created with `spawn`, `spawnAt` or `supervisedSpawnAt` are all defined as `Closure (Par ())`.

```
1 type Task = Either (Closure SupervisedSpark) (Closure (Par ()))
```

Listing 5.4: Definition of a Task

The definition of `SupervisedSpark` is in Listing 5.5. Closures of this structure migrate between nodes, with the actual task expression within it on line 3. It also has a reference to the `IVar` that will be filled with the value of evaluating the task as `remoteRef` on line 4. Finally, the replication number for this task is `thisReplica` on line 5. This value is included in `REQ` and `ACK` message sent to a spark's supervisor, to ensure location tracking is not invalidated.

```
1 -- | Remote representation of supervised future task
2 data SupervisedSpark =
3   SupervisedSpark { clo         :: Closure (Par ())
4                   , remoteRef   :: TaskRef
5                   , thisReplica :: Int }
```

Listing 5.5: Remote Representation of Supervised Future Task

5.1.2 Guard Posts

Each node has a guard post. A guard post serve two purposes: first, to suspend a spark until authorisation of its migration is granted; second, to discard obsolete sparks. For each spark that enters a guard post, an authorisation request is made for its migration with `REQ` (Section 3.5.1). One check that is carried out by the supervisor is that the spark is tagged with the highest replication number of its corresponding future (Section 3.5.3). This authorisation check is shown in Algorithms 4, 8 and 5 in Section 3.5.4. If it is authorised, the spark is scheduled to the thief. If not, it is pushed back into sparkpool local to the guard post. It is simply discarded if identified as an *obsolete* replica.

The guard post data structure is in Listing 5.6. A `GuardPost` on line 1 may be occupied with a guarded spark, or is empty i.e. a `Nothing` value. It records the thief in `destinedFor` (line 4). An `AUTH` message includes the destination of the spark. This is checked against `destinedFor` as a sanity check. If they do not match, an error is thrown.

```
1 type GuardPost = Maybe OccupiedGuardPost
2 data OccupiedGuardPost =
3   OccupiedGuardPost { guardedSpark :: Closure SupervisedTask
4                     , destinedFor  :: NodeId }
```

Listing 5.6: GuardPost Implementation

5.2 HdpH-RS Primitives

Using `spawn` and `spawnAt` invokes the fault oblivious HdpH scheduler. The fault tolerant primitives `supervisedSpawn` and `supervisedSpawnAt` invoke the fault tolerant scheduler (Section 3.5). They match the API of `spawn` and `spawnAt`, allowing programmers to trivially opt in (or out) of fault tolerant scheduling. The original HdpH primitives `spark` and `pushTo` [114] are demoted to internal scheduling functions in the implementation of the spawn family of primitives.

With the introduction of the spawn family of primitives, programmers do not create and write to `IVar`s directly. Listing 5.7 show the implementation of future creation. The creation of supervised futures involves 2 steps. For non-supervised futures, there is only 1. Non-supervised future creation is straight forward, and is done using `mkSpawnClo` on line 3. A new `IVar` is created on line 8, and globalised on line 9. A task is created on line 10, using `spawn_abs` function on line 14. It applies the value of evaluating the user-specified task expression to an `rput` call on the globalised `IVar`. This task and the empty `IVar` are returned to the function caller, either `spawn`, `spawnAt` or `supervisedSpawnAt`. The `IVar` is then returned for the user to perform a blocking `get` operation.

The `mkSupervisedSpawnClo` on line 3 performs two steps. First, it creates and globalises an `IVar` as before. The `glob` operation reserves a placeholder in the registry, to insert the supervised `IVar` when it is constructed. The corresponding task is then constructed. It takes a user expression, and writes the value to globalised `IVar` with `rput`. Lastly, the supervised `IVar` is constructed as a `SupervisedFutureState` on line 34. It contains the task, the scheduling choice (either `Sparked` or `Threaded`), a replica value of 0, and a location tracking state of `InTransition` if the task was sparked with `supervisedSpawn`, or `OnNode` if it was eagerly placed with `supervisedSpawnAt`. This empty supervised future is inserted in to the registry at the reserved index location.

The implementation of the spawn primitives are shown in Listing 5.8. The implementations of `spawn` (line 1) uses `spark` internally on line 4 to add the task to the local sparkpool. The implementation of `spawnAt` (line 19) and `supervisedSpawnAt` (line 25) uses `pushTo` internally, to push the task to the target node. In these 3 cases, the scheduled expression is `Right (Closure (Par ()))` with either `spark` or `pushTo` on lines 4, 22 and 28.

The implementation of `supervisedSpawn` (line 7) uses `mkSupervisedSpark` on line 15 to add supervision state in to a `SupervisedSpark` structure. The scheduled task is `Left (Closure SupervisedSpark)` with `sparkSupervised` on line 12.

```
1  -- | Creation of non-fault tolerant futures and tasks.
2  --   Used by 'spawn' and 'spawnAt'.
3  mkSpawnedClo :: Closure (Par (Closure a)) -- task from user application
4               → Par (Closure (Par ()),     -- task to be scheduled
5                       IVar (Closure a),    -- IVar to be filled by evaluating closure
6                       GIVar (Closure a))   -- handle to identify IVar & scheduled task
7  mkSpawnedClo clo = do
8    v ← new
9    gv ← glob v
10   let clo' = $(mkClosure [| spawn_abs (clo, gv) |])
11   return (clo',v,gv)
12
13 -- | Executed by the node that converts task to a thread.
14 spawn_abs :: (Closure (Par (Closure a)), GIVar (Closure a)) → Par ()
15 spawn_abs (clo, gv) = unClosure clo »= rput gv
16
17 -- | Creation of fault tolerant supervised futures and tasks.
18 --   Used by 'supervisedSpawn' and 'supervisedSpawnAt'.
19 mkSupervisedSpawnedClo
20              :: Closure (Par (Closure a)) -- task from user application
21              → Scheduling      -- Sparked or Pushed
22              → CurrentLocation -- (OnNode here) if sparked, (OnNode target) if pushed
23              → Par (Closure (Par ()),  -- task to be scheduled
24                      IVar (Closure a),  -- IVar to be filled by evaluating closure
25                      GIVar (Closure a)) -- handle to identify IVar & scheduled task
26 mkSupervisedSpawnedClo clo howScheduled currentLocation = do
27   v ← new
28   gv ← glob v
29   let clo' = $(mkClosure [| spawn_abs (clo, gv) |])
30   v' ← newSupervisedIVar clo'          -- create supervised IVar
31   io $ superviseIVar v' (slotOf gv) -- insert supervised IVar in place of placeholder v
32   return (clo',v',gv)
33  where
34    newSupervisedIVar :: Closure (Par ()) → IO (IVar a)
35    newSupervisedIVar clo' =
36      let localSt = SupervisedFutureState
37            { task = clo'
38            , scheduling = howScheduled
39            , location = currentLocation
40            , newestReplica = 0 }
41      io $ newIORef $ Empty { blockedThreads = [] , taskLocalState = Just localSt }
```

Listing 5.7: Creation of Futures and Supervised Futures

5.3 Recovering Supervised Sparks and Threads

When a supervisor receives a `DEADNODE` message indicating a node failure (Section 5.5.4), it may replicate tasks if their liveness is at risk. This is decided by Algorithm 10 in Section 3.5.4, and implemented as `vulnerableEmptyFutures` in Listing 5.2. It uses `replicateSpark` and `replicateThread` in Listing 5.9, the implementations for which are in Appendix A.7. Both return a `Maybe` type, due to a potential race condition whereby

```
1  spawn :: Closure (Par (Closure a)) → Par (IVar (Closure a))
2  spawn clo = do
3    (clo',v,_) ← mkSpawnedClo clo
4    spark clo' -- sparks (Right clo')
5    return v
6
7  supervisedSpawn :: Closure (Par (Closure a)) → Par (IVar (Closure a))
8  supervisedSpawn clo = do
9    here ← myNode
10   (clo',v,gv) ← mkSupervisedSpawnedClo clo Sparked (OnNode here)
11   let supervisedTask = mkSupervisedSpark clo' gv
12   sparkSupervised supervisedTask -- sparks (Left supervisedTask)
13   return v
14  where
15    mkSupervisedSpark :: Closure (Par ()) → GIVar a → Closure SupervisedSpark
16    mkSupervisedSpark closure (GIVar gv) = toClosure
17      SupervisedSpark { clo = closure , remoteRef = taskHandle gv , thisReplica = 0 }
18
19 spawnAt :: Closure (Par (Closure a)) → NodeId → Par (IVar (Closure a))
20 spawnAt clo target = do
21   (clo',v,_) ← mkSpawnedClo clo
22   pushTo clo' target -- pushes (Right clo') to target
23   return v
24
25 supervisedSpawnAt :: Closure (Par (Closure a)) → NodeId → Par (IVar (Closure a))
26 supervisedSpawnAt clo target = do
27   (clo',v,_) ← mkSupervisedSpawnedClo clo Pushed (OnNode target)
28   pushTo clo' target -- pushes (Right clo') to target
29   return v
```

Listing 5.8: Implementation of the Spawn Family

another local scheduler or node writes a value to the `IVar` during the local recovery operation. If the `IVar` becomes full, then a `Nothing` value is returned indicating a full `IVar` and no recovery action needs taking.

```
1  replicateSpark  :: IVar a → IO (Maybe (SupervisedSpark m))
2  replicateThread :: IVar a → IO (Maybe (Closure (Par ())))
```

Listing 5.9: Replicating Sparks & Threads in Presence of Failure

1. The `replicateSpark` and `replicateThread` functions both takes an `IVar` as an argument. The `DEADNODE` handler (Appendix A.6) has determined the safety of the corresponding task to be at risk as a consequence of node failure.

2. It increments the replication number in the `IVar`.

ThreadM
SparkM
CommM
IO

Table 5.3: HdpH-RS Runtime System Monad Stack

3. A new replica is returned, and scheduled according the `recover_spark` and `recover_thread` transition rules in the operational semantics (Section 3.4.3).

   (a) If a supervised spark is being recovered, a `SupervisedSpark` is returned and added to the local sparkpool.

   (b) If a thread is being recovered, a `Closure (Par ())` is returned, unpacked with `unClosure`, and added to a local threadpool.

5.4 HdpH-RS Node State

Node state in encapsulated in a monad stack in HdpH-RS, shown in Table 5.3. This monad stack is inherited from HdpH. This Section describes where the state within each monad has been extended for fault tolerance. The `CommM`, `SparkM` and `ThreadM` monads are all synonyms for the reader monad transformer `ReaderT` [92], encapsulating the mutable state within each associated module. Whilst the Reader monad transformer provides a read-only environment to the given monad, mutability in the HdpH-RS monads is achieved with `IORef`s in this read-only environment. This section describes the mutable state in each monad, paying close attention to the implementation of fault tolerance in the designs in Chapter 3.

5.4.1 Communication State

The `CommM` monad sits on top of the `IO` monad. It encapsulates the distributed virtual machine state, in Listing 5.10. The queue of messages received by an endpoint is stored in `s_msgQ` on line 8, implemented as a channel of lazy bytestrings. The state of the distributed virtual machine allows remote nodes to be removed when their failure is identified. The nodes in the distributed virtual machine is stored in a mutable field `s_nodes_info` on line 6. It is modified in two circumstances.

1. When the HdpH-RS virtual machine is bootstrapped, node discovery is achieved with UDP multicast between all hosts in a cluster. This list of nodes is written to the `IORef` in `s_nodes_info`.

2. When a connection is lost with a node, the `s_nodes_info IORef` is atomically modified. The lost node is removed from the list `s_allNodes` (line 11) and `s_nodes` decremented (line 12). The `s_allNodes` is used in the implementation of the `allNodes` function in the HdpH-RS API.

```
1  -- | CommM is a reader monad on top of the IO monad; mutable parts of the state
2  --   (namely the message queue) are implemented via mutable references.
3  type CommM = ReaderT State IO
4
5  data State =
6    State { s_nodes_info :: IORef VMNodes, -- active nodes in VM
7            s_myNode     :: NodeId,        -- currently executing node
8            s_msgQ       :: MessageQ, }    -- queue holding received messages
9
10 data VMNodes =
11   VMNodes { s_allNodes :: [NodeId], -- alive nodes in distributed virtual machine
12             s_nodes    :: Int }     -- number of alive nodes
```

Listing 5.10: HdpH-RS CommM Monad State

5.4.2 Sparkpool State

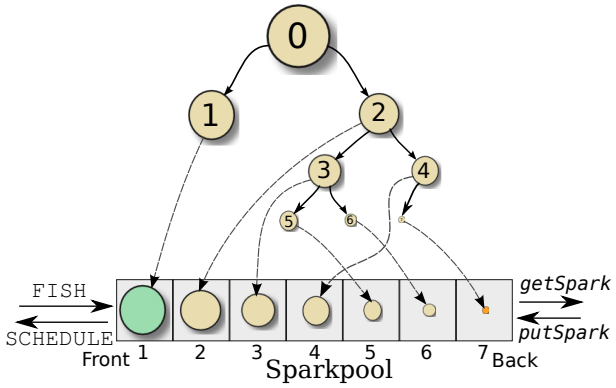


Figure 5.4: Sparkpool Deque, Implemented as `DequeIO Task` in `s_pool` (Listing 5.11)

In many divide-and-conquer patterns, tasks generated early on are bigger than later tasks. The early tasks are often sub-divided many times before work is executed. To reduce communication costs, it is desirable to send large tasks to remote nodes, so that remote nodes can generate work themselves, rather than fishing frequently from other nodes. The access to the sparkpool queue encourages large tasks to be stolen and small tasks to stay local to the generating node, as shown in Figure 5.4. New sparks generated with `spawn` or `supervisedSpawn` are pushed to the back of the queue. The node hosting

the sparkpool steals work from its own sparkpool from the back of the queue. A busy node that receives a FISH message from a thief pops a spark from the front of the sparkpool and replies with a SCHEDULE message containing that spark.

```
1  -- | 'SparkM ' is a reader monad sitting on top of the 'CommM' monad
2  type SparkM = ReaderT State CommM
3
4  -- spark pool state (mutable bits held in IORefs and the like)
5  data State =
6    State { s_pool       :: DequeIO Task,          -- actual spark pool
7            s_guard_post :: IORef GuardPost,  -- spark suspended for authorisation
8            s_sparkOrig  :: IORef (Maybe NodeId),  -- origin of most recent spark recvd
9            s_fishing    :: IORef Bool,            -- True iff FISH outstanding
10           s_noWork     :: ActionServer }         -- for clearing "FISH outstndg" flag
```

Listing 5.11: HdpH-RS SparkM Monad State

The SparkM monad sits on top of the CommM monad. It encapsulates the sparkpool state, in Listing 5.11. The sparkpool itself is s_pool on line 6. It is a double-ended queue that contains tasks of type Task, holding both supervised and unsupervised sparks. The guard post s_guard_post on line 7 is either empty or holds one supervised spark that is held for an authorised migration. The fishing protocol is optimised to fish from the node it has most recently received a SCHEDULE message, in the hope it has more on offer. The s_sparkOrig field holds this information on line 8. The s_fishing boolean on line 9 is used to indicate whether a node is in the process of a work stealing i.e. waiting for a reply to a FISH message. The s_noWork field corresponds to the waitingFishReplyFrom field in typedef WorkerNode in the Promela model (Section 4.3.3). It is reset when a NOWORK message is received, allowing a node to fish for sparks once again.

5.4.3 Threadpool State

The ThreadM monad sits on top of the SparkM monad. It encapsulates the threadpool state, in Listing 5.12. In the benchmark executions in Chapter 6, the number of threadpools matches the number of utilised cores per node. The state on line 5 is a list of threadpools. Each threadpool is a doubled-ended queue. Access to the threadpool is controlled in the same way as the sparkpool. Each scheduler accesses its own threadpool from the back. Schedulers are able to steal from the front of other threadpools on the same shared-memory node, when their own threadpool is empty.

```
1  -- | 'ThreadM' is a reader monad sitting on top of the 'SparkM' monad
2  type ThreadM = ReaderT State SparkM
3
4  -- | thread pool state (mutable bits held in DequeIO)
5  type State = [(Int, DequeIO Thread)]  -- list of actual thread pools,
```

Listing 5.12: HdpH-RS ThreadM Monad State

5.5 Fault Detecting Communications Layer

5.5.1 Distributed Virtual Machine

The mechanism for peer discovery is different for each distributed environment a user is working with. Using a cluster with MPI, a program is *told* about its peers. Using other transports like TCP, a program must *discover* its peers. In the Cloud Computing setting, a program may *start* other peers by instantiating new virtual machines. The HdpH-RS approach is peer *discovery* with UDP.

Programs that use MPI have access to API calls to obtain a list of peers. The `MPI_Comm_size(..)` call looks up all MPI ranks, and `MPI_Comm_rank(..)` returns the rank of the calling process. The first HdpH release [114] used an MPI backend, and used these MPI calls to obtain the list of peers. Section 2.3.5 describes the fault tolerance limitations of MPI — any fault will typically bring down the entire communicator, making this an unsuitable backend for HdpH-RS. Socket based transports are more suitable. HdpH-RS uses a TCP-based transport layer.

One drawback of moving HdpH-RS away from MPI is that an additional node discovery step must be taken. The HdpH-RS Comm module uses UDP multicast for node discovery. Once the distributed virtual machine is constructed, it is stored as mutable state on each node (Section 5.4) and the scheduler is started. If the failure of remote nodes are detected, they are removed from the peers list on each node. The distributed virtual machine software stack is shown in Figure 5.5.

5.5.2 Message Passing API

The `network-transport-tcp` library [45] is used in the HdpH-RS Comm module for sending and receiving messages. It is also used for detecting lost connections to propagate `DEADNODE` messages to the `Scheduler` and `Sparkpool` modules.

The Comm module additionally provides a simple virtual machine API in Listing 5.13. It exposes `myNode` on line 2, which is similar to `MPI_Comm_rank(..)`, and `allNodes` on line 5 which is analogous to MPI's `MPI_Comm_size(..)`.

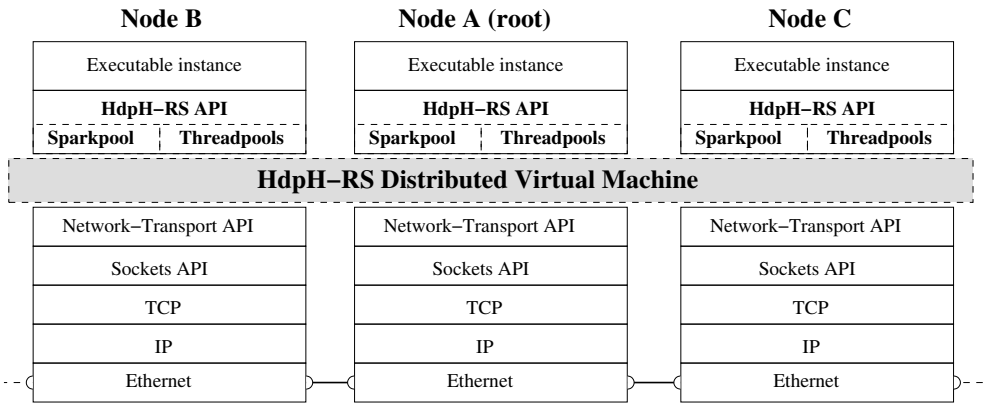


Figure 5.5: HdpH-RS Distributed Virtual Machine Software Stack

```
1  -- The currently executing node.
2  myNode   :: CommM NodeId
3
4  -- List of all nodes in the virtual machine.
5  allNodes :: CommM [NodeId]
6
7  -- True iff the currently executing node is the main node.
8  isMain   :: CommM Bool
9
10 -- |Send a HdpH-RS payload message.
11 send     :: NodeId → Message → CommM (Either (NT.TransportError NT.SendErrorCode) ())
12
13 -- | Receive a HdpH-RS payload message.
14 receive  :: CommM Message
```

Listing 5.13: HdpH-RS Comm module API

The HdpH-RS `send` and `receive` functions on lines 11 and 14 of Listing 5.13 are lightweight wrappers over the corresponding functions in the `network-transport` API which is shown in Listing 5.14. In this API, the `receive` function returns an `Event` (line 8). An event may be a normal payload message with the `Received` constructor on line 9. These are normal HdpH-RS messages from Section 5.5.3. The `EventConnectionLost` constructor on line 19 is translated to a `DEADNODE` message in HdpH-RS. The `EventErrorCode`s are documented in Appendix A.5.

5.5.3 RTS Messages

The `receive` function in the HdpH-RS Comm module returns HdpH-RS messages in Listing 5.15. These messages were first introduced and described in Section 3.5.

The `PUSH` message on line 1 is used to eagerly schedule tasks with `spawnAt` and `supervisedSpawnAt`, and also for `rput` calls to transmit the value into an `IVar` future.

```
1  -- | send a message on a connection.
2  send :: Connection → [ByteString] → IO (Either (TransportError SendErrorCode) ())
3
4  -- | endpoints have a single shared receive queue.
5  receive :: EndPoint → IO Event
6
7  -- | Event on an endpoint.
8  data Event =
9          Received !ConnectionId [ByteString]
10       | ConnectionClosed !ConnectionId
11       | ConnectionOpened !ConnectionId Reliability EndPointAddress
12       | ReceivedMulticast MulticastAddress [ByteString]
13       | EndPointClosed
14       | ErrorEvent (TransportError EventErrorCode)
15
16 -- | Error codes used when reporting errors to endpoints (through receive)
17 data EventErrorCode = EventEndPointFailed
18                     | EventTransportFailed
19                     | EventConnectionLost EndPointAddress
```

Listing 5.14: Network.Transport API

The following messages are used internally by the `Scheduler` and `Sparkpool` modules: `FISH`, `SCHEDULE`, `NOWORK`, `REQ`, `AUTH`, `DENIED`, `OBSOLETE` and `ACK`. Finally, the `DEADNODE` message is generated by the `Comm` module when node failure is detected.

5.5.4 Detecting Node Failure

HdpH-RS Error Events

When the network abstraction layer detects TCP connection loss, it propagates this as a `EventConnectionLost` message in a `ErrorEvent` constructor to HdpH-RS. The implementation of the `receive` function used by the scheduler is shown in Appendix A.8. It inspects each event received from the network abstraction layer, and does the following:

1. If a bytestring is received in a `Received` message, then it is unpacked and returned to the HdpH-RS scheduler as a normal HdpH-RS message.

2. If an `ErrorEvent` is received, then the lost connection is inspected for 2 cases:

   (a) **The connection with the root node is lost** In this case, the local node can play no further part in the current program execution. It terminates itself as a node instance on line 17. Connectivity with the root node may be lost either because the root node has failed, or through network partitioning (Section 3.5.5).

```
1  data Msg = PUSH         -- eagerly pushing work
2               Task       -- task
3           | FISH         -- looking for work
4               !NodeId    -- thief sending the FISH
5           | SCHEDULE     -- reply to FISH sender (when there is work)
6               Task       -- spark
7               !NodeId    -- victim sending the SCHEDULE
8           | NOWORK       -- reply to FISH sender (when there is no work)
9           | REQ          -- request for a spark
10              TaskRef    -- The globalised spark pointer
11              !Int       -- replica number of task
12              !NodeId    -- the victim it would send the SCHEDULE
13              !NodeId    -- the thief that would receive SCHEDULE
14          | AUTH
15              !NodeId    -- thief to send SCHEDULE to
16          | DENIED
17              !NodeId    -- thief to return NOWORK to
18          | ACK          -- notify supervisor that spark has been received
19              TaskRef    -- The globalised spark pointer
20              !Int       -- replica number of task
21              !NodeId    -- thief that is sending ACK to supervisor
22          | DEADNODE     -- a node has died
23              !NodeId    -- which node has died
24          | OBSOLETE     -- obsolete task copy (old replica number)
25              !NodeId    -- thief waiting for guarded spark, to receive NOWORK
26          | HEARTBEAT    -- keep-alive heartbeat message
```

Listing 5.15: Scheduling Messages in HdpH-RS

(b) **The connection with a non-root node is lost** In this case, the remote node is removed from the local virtual machine. This is done by sending a `DEADNODE` message to the scheduler on line 25. the scheduler will remove the remote node from the distributed VM, and decrements the `nodes` parameter, which is the sum of all nodes in the distributed VM.

Propagating Error Messages

Failure detection in HdpH-RS depends on the `network-transport-tcp` implementation [45], and the failure detection on TCP connections. There is a three-way handshake to control the state of a TCP connection [133]. The TCP handshake happens at the Operating System level, beneath the level of the `network-transport-tcp` Haskell library. A sequence flag `SYN` is used to initialise a connection. A TCP connection termination sequence is shown in Figure 5.6. A finish flag `FIN` is used to cleanly terminate a connection and an acknowledge flag `ACK` is used to acknowledge received data [180].

TCP is an idle protocol, so if neither side sends any data once a connection has been established, then no packets are sent over the connection [38]. The act of receiving data

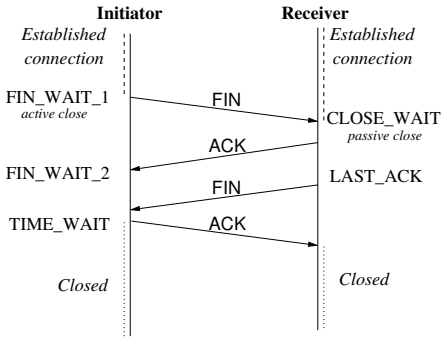


Figure 5.6: TCP Handshake for Closing Connections

is completely passive in TCP, and an application that only reads from a socket cannot detect a dropped connection. This scenario is called a *half-open connection* [148]. When a node sends data to the other side it will receive an `ACK` if the connection is still active, or an error if it is not. Broken connections can therefore be detected with transmission attempts.

Half open TCP connections can be caused by Operating System processes or nodes crashing. When a process is terminated abnormally, there will not be the usual `FIN` message to terminate a connection. Whilst an Operating System may send a `FIN` on behalf of the process, this is Operating System dependent. If the failure is a hard node crash, there will certainly be no notification sent to the other side that the connection has been lost.

In order to discover lost TCP connections, two options are available [38]. The first is to add explicit keep-alive messages to an application protocol. The second is to assume the worst, and implement timers for *receiving* messages on connections. If no packets are received within the timeout period, a connection may be regarded as lost.

As architectures scale to thousands of nodes, error propagation through work stealing message transmissions cannot be relied upon. The HdpH-RS keep-alive messages is a guarantee of periodic traffic between nodes independent of work stealing messages, enabling nodes to discover failure by discovering lost connections.

Keep-Alive Messages in HdpH-RS

Whilst the transmission of work stealing messages will probably trigger timely TCP failures for smaller architectures, there is a high failure detection latency in larger networks. This has an important implication for performance in HdpH-RS. Take an example where node A creates a supervised spark $spark_1$ and `IVar` i_1 with the execution of `supervisedSpawn`. Node B fishes $spark_1$, and later suffers a power outage. Node A may not receive a TCP `FIN` message from B due to the sudden failure. Node A does not send

any work stealing messages to B, but is waiting for the value of evaluating $spark_1$ to be written to i_1. To ensure a more reliable failure detection of B, node A needs some other message transmission mechanism than just work stealing.

The keep-alive implementation in HdpH-RS is simple. A `keepAliveFreq` parameter has been added to the RTS configuration parameters, of the scheduler. This flag is documented in Section 6.2, along with examples of using it. It is an Integer value that allows the user to state N, the time in seconds between each keep-alive. If $N > 0$ then a keep-alive server is enabled on each node. This server is forked into a thread when the scheduler is initialised. When the frequency delay expires, a node broadcasts a keep-alive to every node it is currently connected to. As TCP failures are detected on send attempts, the keep-alive is silently ignored on the receiving end. The heartbeats in HdpH-RS is shown in Listing 5.16. After N seconds, a node broadcasts a `HEARTBEAT` to all other nodes (line 2). When a node receives a `HEARTBEAT` message, it is silently ignored (line 11).

For small architectures, heartbeats are unlikely to be the trigger that detects failure. On large architectures, work stealing messages between any two nodes are less likely to be transmitted within the keep-alive frequency, so the keep-alive messages are an important mechanism for failure detection.

```
1  -- | broadcasting periodic heartbeats.
2  keepAliveServer :: Int → [NodeId] → IO ()
3  keepAliveServer delaySeconds nodes = forever go
4    where
5      go = do
6         threadDelay (delaySeconds * 1000000)
7         mapM_ sendHeartBeat nodes
8      sendHeartBeat node = void $ send node (encode HEARTBEAT)
9
10 -- | receive heartbeats & ignore them.
11 handleHEARTBEAT :: Msg RTS → RTS ()
12 handleHEARTBEAT HEARTBEAT = return ()
```

Listing 5.16: Sending & Receiving Periodic HEARTBEAT Messages

The main drawback to this failure detection strategy is the dependency on connection oriented protocols like TCP. There are two main weaknesses. First, the failure detection strategy of using connection-oriented transmission attempts would not work for connectionless protocols like UDP [131]. Second, the design assumes a fully connected network. Every node has a persistent connection with every other node. The scalability limitations of TCP connections are well known [76].

- **File descriptors** Each node has a maximum number of file descriptors to facilitate concurrent connections. It is 1024 by default on Linux. It is specified in

`/proc/sys/fs/file-max`, though can easily be changed.

- **Socket buffers** Each TCP connection contain a socket receive and send buffer. A receive buffer may be in the $87kb$ region (in file `/proc/sys/net/ipv4/tcp_rmem`) and write buffers in the $16kb$ region (in file `/proc/sys/net/ipv4/tcp_wmem`). An Operating System allocates memory for socket buffers, which limits the number of theoretically possible TCP connections.

The author is in discussion [88] with the `network-transport` authors on a generalised failure detection for distributed Haskells. A failure detection mechanism has not yet been added to the library. The proposed generalised strategy is to use passive heartbeat timeouts. That is, every node broadcasts a timeout, and expects a heartbeat message from all other nodes. If a heartbeat is not received from a remote node within a given timeout threshold, it is assumed to have failed. It is the opposite to HdpH-RS, which detects failure actively on the heartbeat broadcaster, not passively on the receiver.

The generalised fault detection design for distributed Haskells does have some drawbacks. First, network congestion may delay message delivery that results in false-positives in failure detection [191]. Second, the latency of failure detection is higher. It is at least the size of the timeout window + the delay between heartbeats (Section 2.2.3).

5.6 Comparison with Other Fault Tolerant Language Implementations

The implementation of fault tolerance in HdpH-RS shares many techniques with other fault tolerant programming languages and distributed schedulers. Replication (Section 2.2.3) is the key recovery mechanism in HdpH-RS. It is a tactic used in the supervision behaviours of Erlang [7], and is ingrained in the Google MapReduce model [49], such as in Hadoop [183].

5.6.1 Erlang

The supervision approach in Erlang is a strong influence on the implementation of HdpH-RS. Below are four distinctions between the performance of Erlang and HdpH in the absence of faults, and the recovery in Erlang and HdpH-RS in the presence of faults.

Handling failures The failure recovery in HdpH-RS is akin to the Erlang OTP supervision behaviours. The user does not need to handle failures programmatically. However, when the `monitor` and `link` Erlang primitives are used directly, it is the responsibility of the programmer to recover from faults.

Recovering stateful computations Erlang has better support for recovering non-idempotent computations, using the restart strategies and frequencies of the supervision behaviour in Erlang OTP. HdpH-RS does not support the recovery of non-idempotent tasks, and is designed for evaluating pure expressions that are of course idempotent.

Load balancing Support for load balancing is more powerful in HdpH and HdpH-RS than in Erlang. A work stealing mechanism in Erlang could be thought of as HdpH-RS without sparkpools and only threadpools — once an Erlang process is spawned, it cannot migrate to another node. This makes Erlang less suitable than HdpH-RS for some classes of computation, where parallelism is highly irregular. Parallel symbolic computing is one example.

Programming errors Erlang is an untyped language, allowing many programming errors to go unnoticed at compile time [174]. Such typing error can introduce faults at runtime. A type system has been proposed [119], though is not often used. Only a subset of the language is type-checkable, the major omission being the lack of process types [6]. In contrast, the Haskell host language for HdpH-RS is strongly typed, eliminating a large class of software bugs at compile time.

5.6.2 Hadoop

Hadoop is a popular MapReduce implementation. MapReduce is a programming model and an associated implementation for processing and generating large data sets [49]. If Hadoop is used using the MapReduce interface directly, a programmer only defines a *map* and a *reduce* function, and these are automatically parallelisable.

To relate the programming model to HdpH-RS, the MapReduce model is in fact an algorithmic skeleton. It has been implemented in HdpH-RS as 2 of 10 parallel skeletons. First an implicit `parMapReduceRangeThresh` skeleton, and second an explicit `pushMapReduceRangeThresh` skeleton. They are used in the implementation of the Mandelbrot benchmark in Section 6.3.1. The failure recovery in Hadoop is task replication, the same as Erlang and HdpH-RS. The failure recovery in HdpH-RS can be compared to Hadoop in three ways:

Failure detection latency Failure detection latency in Hadoop is 10 minutes by default in order to tolerate non-responsiveness and network congestion. A slave sends a heartbeat to the master node every 3 seconds. If the master does not receive a heartbeat from a given slave within a 10 minute window, failure is assumed [55]. In contrast, the failure detection latency in HdpH-RS is a maximum of 5 seconds by default, and can be modified by the user.

Supervision Bottleneck A master node supervises the health of all slave nodes

in Hadoop. In contrast, the HdpH-RS architecture supports hierarchically nested supervisors. This is achieved with either recursive `supervisedSpawn` or `supervisedSpawnAt` calls, or by using the MapReduce or divide-and-conquer skeletons. This means that supervision and task replication responsibilities are distributed across the entire architecture in HdpH-RS, and not centrally coordinated like Hadoop.

Unnecessary task replication The output of map tasks are stored to disk locally in Hadoop. In the presence of failure, completed map tasks are re-scheduled, due to the loss of their results. This is in contrast to HdpH-RS, where the resulting values of evaluating task expressions is transmitted with `rput` as soon as they are calculated.

5.6.3 GdH Fault Tolerance Design

The design of a new RTS level of fault tolerance for Glasgow distributed Haskell (GdH) [173] has been proposed, but not implemented. The design augments the GdH RTS with error detection and error recovery.

The failure detection is similar to the HdpH-RS detection. It is designed to rely on the eager node failure detection from its PVM [15] network layer. As in HdpH-RS, intermittent node failure is managed by ignoring future message from the faulty node. When the transport layer broadcasts the node failure, future messages sent by a previously faulty node are discarded — by the scheduler in the case of GdH, and by `network-transport-tcp` [45] library in the case of HdpH-RS.

Simultaneous failure recovery in the GdH design is similar to the HdpH-RS implementation. In both, one node is distinguished as the root node, which starts and terminates the program. If a network is split in to two or more parts, the partition containing the root node will restart the pure computations from the lost partitions.

In order to replicate pure computations in the presence of failure, both the GdH design and HdpH-RS store task copies on the creating node. The store of these tasks is defined as a *backup heap* in GdH. The back-up task copies in HdpH-RS are stored within their corresponding empty future.

The GdH fault tolerance design include some techniques borrowed from Erlang, that have not been adopted in HdpH-RS. One example is continued service. A computation cannot be restarted more than a fixed number of times before raising an exception in the GdH design, similar to the child process restart frequency in Erlang OTP. A message is not re-transmitted more than a fixed number of times before raising an exception, preventing livelock. Finally, nodes can be added during the execution of programs, to replace failed nodes. None of these 3 features have been implemented in HdpH-RS.

5.6.4 Fault Tolerant MPI Implementations

Most scientific applications are written in C with MPI [98]. The original MPI standards specify very limited features related to reliability and fault tolerance [73]. Based on early MPI standards, an entire application is shutdown when one of the executing processors experiences a failure. As discussed in Section 2.3.5, MPI implementations that include fault tolerant take one of two approaches. Either they hide faults from the user, or propagate them for the user to recover from faults programmatically. Some fault tolerant MPI implementations mask faults, but thereafter support a reduced set of MPI operations. This masking of failures is the same approach as HdpH-RS, with the difference that no programming primitives are disabled by faults.

Chapter 6

Fault Tolerant Programming & Reliable Scheduling Evaluation

This chapter demonstrates how to program with reliable scheduling and gives a performance evaluation of HdpH-RS. Section 6.1.1 demonstrates how to write fault tolerance programs with HdpH-RS. The parallel skeletons from HdpH have been ported to HdpH-RS (Section 6.1.2), adding fault tolerance by implementing them using the `supervisedSpawn` and `supervisedSpawnAt` primitives. Section 6.2 describes how to launch HdpH-RS programs on clustered architectures, and how to configure the HdpH-RS RTS for fault tolerance and performance tuning. Section 6.3.1 describes the five benchmarks used to evaluate HdpH-RS. Section 6.3.3 describes the two architectures on which HdpH-RS has been measured. One is a 32 node Beowulf cluster providing 224 cores. The other is HECToR, a high performance UK national compute resource, and up to 1400 cores are used to measure the scalability of HdpH-RS.

The supervision overheads of the fault tolerant work stealing protocol (Section 3.5) are compared against the HdpH fault oblivious scheduling in Section 6.4, by measuring the fault tolerant and non-fault tolerant version of three skeletons — parallel-map, divide-and-conquer and map-reduce. The benchmark executions demonstrate the scalability of fault tolerance in HdpH-RS. For example, the Summatory Liouville benchmark demonstrates HdpH-RS speedup of 145 on 224 cores on Beowulf, and a speedup of 751 on 1400 cores on HECToR. The recovery overheads of detecting faults and replicating tasks is measured in Section 6.5 by injecting two types of failure during execution using the HdpH-RS scheduler. The first type simulates simultaneous node loss (Section 6.5.1), which can occur when networks are partitioned. The second type uses a Chaos Monkey implementation in HdpH-RS (Section 6.5.2), to simulate random failure. Unit tests are used ensure that programs using the fault tolerant skeletons terminate with the correct

result in the presence of Chaos Monkey failure injection. The runtime performance of HdpH-RS indicate that lazy on-demand work stealing is more suitable when failure is the common case, not the exception.

6.1 Fault Tolerant Programming with HdpH-RS

This section shows how to program with HdpH-RS primitives and skeletons. The use case is a parallel implementation of Euler's totient function ϕ [102]. It is an arithmetic function that counts the totatives of n, i.e. the positive integers less than or equal to n that are relatively prime to n. Listing 6.1 shows the implementation of ϕ and the sequential sum of totients. It is parallelised in Section 6.1.1 using the HdpH-RS primitives directly, and in Section 6.1.3 using the `parMapSlicedFT` skeleton.

```
1 -- | Euler's totient function (for positive integers)
2 totient :: Int → Integer
3 totient n = toInteger $ length $ filter (λ k → gcd n k == 1) [1..n]
4
5 -- | sequential sum of totients
6 sum_totient :: [Int] → Integer
7 sum_totient = sum ∘ map totient
```

Listing 6.1: Sequential Implementation of Sum Euler

6.1.1 Programming With HdpH-RS Fault Tolerance Primitives

Using the HdpH-RS primitives directly for computing Sum Euler between 0 and 10000 with a slice size of 100 is shown in Listing 6.2. The `dist_sum_totient_sliced` function creates a sliced list of lists on line 5 using the lower and upper bounds and chunk size. For each element in the list, a supervised spark and corresponding `IVar` (the supervised future) is created with `supervisedSpawn` on line 11. The results are summed on line 3. The `main` function on line 16 prints the result 30397486.

6.1.2 Fault Tolerant Parallel Skeletons

Algorithmic skeletons abstract commonly-used patterns of parallel computation, communication, and interaction [39]. The implementation of skeletons manage logic, arithmetic and control flow operations, communication and data exchange, task creation, and synchronisation. Skeletons provide a top-down design approach, and are often compositional [71].

```
1  dist_sum_totient_sliced :: Int → Int → Int → Par Integer
2  dist_sum_totient_sliced lower upper chunksize = do
3    sum <$> (mapM get_and_unClosure =« (mapM spawn_sum_euler $ sliced_list))
4       where
5        sliced_list = slice slices [upper, upper - 1 .. lower] :: [[Int]]
6
7        get_and_unClosure :: IVar (Closure a) → Par a
8        get_and_unClosure = return ∘ unClosure <=< get
9
10 spawn_sum_euler :: [Int] → Par (IVar (Closure Integer))
11 spawn_sum_euler xs = supervisedSpawn $(mkClosure [| spawn_sum_euler_abs (xs) |])
12
13 spawn_sum_euler_abs :: ([Int]) → Par (Closure Integer)
14 spawn_sum_euler_abs (xs) = force (sum_totient xs) >>= return ∘ toClosure
15
16 main = do
17   result ← runParIO conf (dist_sum_totient_sliced0 10000 100)
18   print result -- "30397486"
```

Listing 6.2: Programming with HdpH-RS Primitives Directly

The `supervisedSpawn` and `supervisedSpawnAt` primitives from Section 3.3.2 guarantee the evaluation of a single task — a supervised spark or thread corresponding to a supervised future. Higher-level abstractions built on top of these primitives guarantee the completion of a set of tasks of this type. These abstractions hide lower level details by creating supervised sparks or threads, and supervised futures (`IVars`) dynamically.

Eight parallel skeletons from HdpH have been extended for fault tolerance. HdpH-RS introduces four skeleton patterns to the HdpH skeletons library: `parMapForkM`, `forkDivideAndConquer`, `parMapReduceRangeThresh` and `pushMapReduceRangeThresh`. The first two abstract shared-memory parallel patterns, and the latter two are extended for fault tolerance as `parMapReduceRangeThreshFT` and `pushMapReduceRangeThreshFT`. The HdpH-RS skeletons API is in Appendix A.9. Lazy work stealing skeletons are replaced with supervised lazy work stealing versions by using `supervisedSpawn`. Fault tolerant skeletons that use eager task placement are implemented with `supervisedSpawnAt`. As an example, Listing 6.3 shows the implementation of the fault tolerant parallel-map skeleton `parMapFT`. It uses a `parClosureList` strategy on line 12 which uses the fault tolerant HdpH-RS `supervisedSpawn` primitive within `sparkClosure` on line 17. There are variants of parallel-map skeletons, for slicing and chunking input lists.

Divide-and-conquer is a more elaborate recursive parallel pattern. A fault tolerant `parDivideAndConquerFT` skeleton is shown in Listing 6.4. It is a skeleton that allows a problem to be decomposed into sub-problems until they are sufficiently small, and then reassembled with a combining function. Its use is demonstrated with Queens in Section

```
1  parMapFT :: (ToClosure a)
2           ⇒ Closure (Strategy (Closure b))
3           → Closure (a → b)
4           → [a]
5           → Par [b]
6  parMapFT clo_strat clo_f xs =
7    do clo_ys ← map f clo_xs `using` parClosureList clo_strat
8       return $ map unClosure clo_ys
9         where f = apC clo_f
10              clo_xs = map toClosure xs
11
12 parClosureList :: Closure (Strategy (Closure a)) → Strategy [Closure a]
13 parClosureList clo_strat xs = mapM (sparkClosure clo_strat) xs »= mapM get
14
15 sparkClosure :: Closure (Strategy (Closure a)) → ProtoStrategy (Closure a)
16 sparkClosure clo_strat clo =
17   supervisedSpawn $(mkClosure [| sparkClosure_abs (clo, clo_strat) |])
18
19 sparkClosure_abs :: (Closure a,Closure (Strategy (Closure a))) → Par (Closure a)
20 sparkClosure_abs (clo, clo_strat) = (clo `using` unClosure clo_strat) »= return
```

Listing 6.3: Fault Tolerant Parallel Map Using `supervisedSpawn` on Line 17

6.4.2. The implementation of Queens is in Appendix A.11.4.

```
1  parDivideAndConquerFT
2      :: Closure (Closure a → Bool)                      -- isTrivial
3      → Closure (Closure a → [Closure a])                -- decomposeProblem
4      → Closure (Closure a → [Closure b] → Closure b)    -- combineSolutions
5      → Closure (Closure a → Par (Closure b))            -- trivialAlgorithms
6      → Closure a                                        -- problem
7      → Par (Closure b)
```

Listing 6.4: Divide & Conquer HdpH-RS Skeleton

MapReduce is another recursive pattern that decomposes large tasks in to smaller tasks that can be evaluated in parallel. A fault tolerant `parMapReduceRangeThreshFT` skeleton is shown in Listing 6.5. It is adapted from the monad-par library [117], extended for distributed-memory scheduling with HdpH-RS. It takes a `Integer` threshold value, and an inclusive `Integer` range over which to compute. A map function is used to compute one result from an `Integer` input, and a reduce function to combine the result of two map functions. Lastly, it takes an initial value for the computation. Its use is demonstrated with Mandelbrot in Section 6.4.2. The implementation of Mandelbrot is in Appendix 6.4.2.

The APIs for the lazy scheduling skeletons (that use `spawn` and `supervisedSpawn` under the hood) are identical for fault tolerant and non-fault tolerant execution. The

```
1  parMapReduceRangeThreshFT
2    :: Closure Int                                          -- threshold
3    → Closure InclusiveRange                                -- range to calculate
4    → Closure (Closure Int → Par (Closure a))               -- compute one result
5    → Closure (Closure a → Closure a → Par (Closure a)) -- reduce two results
6    → Closure a                                             -- initial value
7    → Par (Closure a)
8
9  data InclusiveRange = InclusiveRange Int Int
```

Listing 6.5: MapReduce HdpH-RS Skeleton

type signatures for the eager scheduling skeletons are different, with the omission of a list of `NodeId`s in each fault tolerant case. The non-fault tolerant skeletons assume no failure, and are provided a list of `NodeId`s indicating the nodes that will be sent tasks e.g. with `pushDnCFT`. The HdpH-RS skeletons assume failure, and it would not make sense to provide a list of `NodeId`s to a fault tolerant skeleton, as this list may be invalid if some of the nodes in the list fail during execution. Instead the skeleton collects the list of nodes dynamically from the distributed VM, using the `allNodes` function from the `Comm` module (Section 5.1) at the task decomposition phase. Failed nodes are removed from the distributed VM state when their failure is detected, changing the list of `NodeId`s returned from `allNodes`.

6.1.3 Programming With Fault Tolerant Skeletons

Using the HdpH-RS parallel skeleton library to compute the same Sum Euler computation is shown in Listing 6.6. It uses the `parMapSlicedFT` skeleton on line 3, where the slicing of the input list and the application of `spawn_sum_euler` on every element was previously explicit using the `supervisedSpawn` primitive in Listing 6.2, this is now handled by the skeleton. In consequence the skeleton code is smaller, 5 lines rather than 11.

```
1  slice_farm_sum_totient :: Int → Int → Int → Par Integer
2  slice_farm_sum_totient lower upper slices =
3    sum <$> parMapSlicedFT slices $(mkClosure [| totient |]) list
4      where
5        list = [upper, upper - 1 .. lower] :: [Int]
6
7  main = do
8    result ← runParIO conf (slice_farm_sum_totient 0 10000 100)
9    print result -- "30397486"
```

Listing 6.6: Programming with HdpH-RS Skeletons API

`mpiexec` flags	Description
`-disable-auto-cleanup`	Avoids the default MPI behaviour of terminating all processes when one process exits e.g. because of failure.
`-machinefile`	A file name is specified that lists the machine names used for creating node instances.
`-N`	Specifies how many node instances to create.
`<program>`	The user application using the HdpH-RS API, compiled with GHC.
`<program params>`	Arguments to the user application. These are inputs to the user application.
`+RTS -N`	The number of compute capabilities afforded to the user program. This very often is n or $n-1$ (in the case of the HdpH-RS benchmark results), where n is the number of cores on each node processor.

Table 6.1: Arguments and Flags Used By `mpiexec`

6.2 Launching Distributed Programs

The MPI launcher `mpiexec` is used to deploy HdpH-RS program instances to each node. It is useful for starting and terminating multiple process instances on clusters. That is all MPI is used for in HdpH-RS. It is not used as a communications layer (Section 5.5). Once `mpiexec` has deployed program instances to each node, the HdpH-RS transport layer is used for communication between nodes — UDP for peer discovery, then TCP for node to node communication.

```
mpiexec --disable-auto-cleanup -machinefile <hosts> -N n <executable> \
   <HdpH-RS RTS opts> <reliability opts> <program params> +RTS -Nn
```

Listing 6.7: Executing HdpH-RS on Clusters. Described in Tables 6.1 6.2 and 6.3.

An HdpH-RS program can be launched on a distributed environment with the command in Listing 6.7. The MPICHv2 [24] process launcher is used in the experimentation in Section 6.5. MPICHv2 terminates all processes by default when any process terminates before calling `MPI_Finalize`. Thankfully, MPICHv2 features an important flag for fault tolerance, `--disable-auto-cleanup`, which disables this termination behaviour. The author engaged with MPICH2 community [157] for instruction on using this non-standard feature in MPICHv2 version 1.4.1 [169].

RTS flags	Description	Default
`-numProcs`	The number of nodes in the hosts file to be used in the execution of the user programs. The mpiexec launcher uses it to deploy remote program instances on each machine, and the HdpH-RS transport layer needs it (numProcs) to know how many instances to be advertised via UDP.	1
`-scheds`	Threadpools on each node. The HdpH-RS scheduler forks a dedicated scheduler for each threadpool. The GHC runtime additionally needs to be asked for these many cores on each processor, in the `+RTS -N<s>` flag.	1
`-maxFish`	Low sparkpool watermark for fishing. The RTS will send `FISH` messages unless the sparkpool is greater than the `maxFish` threshold.	1
`-minSched`	Low sparkpool watermark for scheduling. The RTS will ignore FISH messages if the size of the sparkpool is less than minSched .	2
`-minFishDly`	After a failed `FISH` (i.e. receiving a `NOWORK` message), this signals the minimum delay in microseconds before sending another `FISH` message.	0.01s
`-maxFishDly`	After a failed FISH , this signals the maximum delay in microseconds before sending another `FISH` message. The scheduler chooses some random time between `minFishDly` and `maxFishDly`.	0.2s

Table 6.2: HdpH-RS Runtime System Flags

Launching Instances of Multithread Haskell Executables

When a Haskell program that uses the HdpH-RS DSL is compiled, an executable file is created. The arguments used by `mpiexec` for deploying Haskell executable instances are described in Table 6.1. The program must be compiled with a `-threaded` flag, allowing a user to pass GHC specific RTS options at runtime using `+RTS`. This is needed in HdpH-RS to specify the number of SMP processing elements to allocate to the executable per node. This value specifies the number of HdpH-RS schedulers for measurements like HdpH-RS runtimes. Throughout this evaluation chapter, the term *node* is used to specify a HdpH-RS node, not a physical host. There is one HdpH-RS node deployed on each host on the Beowulf cluster (Section 6.3.3), and four HdpH-RS nodes deployed on each host on HECToR (Section 6.3.3), one per NUMA region [190].

HdpH-RS Runtime Flags

The HdpH-RS RTS options are used by each node instance. The RTS options enable the user to configure the scheduler for optimal load balancing for their target architecture. The HdpH-RS specific RTS flags are shown in Table 6.2. There is no explicit flag to

Reliability flags	Description
`-keepAliveFreq`	Sets a frequency for broadcasting `HEARTBEAT` messages on every node.
`-killAt`	The length of a comma separated integer list indicates how many nodes should die, and the values in the list indicate when each of those nodes should die.
`-chaosMonkey`	Informs root node to randomly select and poison non-root nodes to die at a specific time, in seconds.

Table 6.3: HdpH-RS Reliability Flags

turn on reliable scheduling. Instead, it is automatically invoked when `supervisedSpawn`, `supervisedSpawnAt` or fault tolerant skeletons are used. A node continues to fish for sparks until its sparkpool holds at minimum of `maxFish` sparks. If a node holds less than `minSched` sparks, it will reply to a `FISH` message with a `NOWORK` reply. If it holds at least `minSched` sparks, it uses the fault tolerant fishing protocol (Section 3.5.4) to initiate a spark migration to the thief.

If a fishing attempt fails, i.e a `NOWORK` message is received, a node will send a `FISH` to a new victim. The time delay from receiving the `NOWORK` to sending a new `FISH` is a randomly chosen value between `minFishDly` and `maxFishDly`. The `maxFishDly` default value in HdpH is 1 second. Fishing hops are disabled in HdpH-RS to avoid deadlocks (Section 3.5.2). The `maxFishDly` in HdpH-RS is reduced to 0.2 seconds to compensate for the removal of hopping.

Reliability and Fault Injection Flags

The HdpH-RS reliability flags are shown in Table 6.3. There are two fault injection facilities in HdpH-RS to simulate failure. They are used for measuring recovery costs in Section 6.5. They simulate single node failure, simultaneous failure e.g. network partitions, and chaotic random failure.

The `killAt` flag allows a user to specify how many failures will occur, and after how many seconds after program execution begins. This can be used for simulating a sequence of node failures e.g. at 5, 10 and 23 seconds. It can also be used to simulate simultaneous failure, such as a network partition occurrence. For example, a user can specify that three nodes will fail at 35 seconds with `-killAt=35,35,35`.

The second mechanism is invoked with a `chaosMonkey` flag, which enables random failure injection, inspired by Netflix's Chaos Monkey [82]. The `chaosMonkey` mechanism is used as a unit test to ensure that HdpH-RS returns a result in chaotic and unreliable environments, and that the result is correct. There are two phases to this mechanism.

Benchmark	Skeleton	Code Origin	Regularity	Sequential code size (lines)
Sum Euler	chunked parallel maps	HdpH [110]	Some	2
Summatory Liouville	sliced parallel map	GUM [77]	Little	30
Fibonacci	divide-and-conquer	HdpH [110]	Little	2
N-Queens	divide-and-conquer	monad-par [117]	Little	11
Mandelbrot	MapReduce	monad-par [117]	Very little	12

Table 6.4: HdpH-RS Benchmarks

First, a random number of nodes are selected to fail during the program execution. Second, a node that has been selected to fail will be poisoned at the start of execution. The poison will take effect within the first 60 seconds of execution. The inputs to the benchmarks in Section 6.5.1 require failure-free execution of little more than 60 seconds. The maximum of 60 second failures is used to assess recovery costs when failure occurs near the beginning and near the end of expected runtime.

The implementations of these failure mechanisms exploit the UDP node discovery in HdpH-RS (Section 5.5.1). The root node poisons a selection of nodes in accordance with the user specified timing set with `killAt`, or randomly if `chaosMonkey` is used. This is achieved by sending poisonous peer discovery UDP messages to other nodes, described in Section 6.5.2

6.3 Measurements Platform

6.3.1 Benchmarks

The runtime performance of HdpH-RS is measured using the five benchmarks in Table 6.4. They are implemented using fault tolerant and non-fault tolerant skeletons, shown with both lazy and eager scheduling. For example, Summatory Liouville is implemented with `parMapSliced`, `pushMapSliced`, `parMapSlicedFT` and `pushMapSlicedFT` (Appendix A.9).

Sum Euler is a symbolic benchmark that sums Euler's totient function ϕ over long lists of integers. Sum Euler is an irregular data parallel problem where the irregularity stems from computing ϕ on smaller or larger numbers.

The Liouville function $\lambda(n)$ is the completely multiplicative function defined by $\lambda(p) = -1$ for each prime p. Summatory Liouville $L(n)$ denotes the sum of the values of the Liouville function $\lambda(n)$ up to n, where $L(n) := \sum_{k=1}^{n} \lambda(k)$.

The Fibonacci function is a well known divide-and-conquer algorithm. It is defined as $f_n = f_{n-1} + f_{n-2}$, where $F_0 = 0, F_1 = 1$. A threshold t is a condition for sequential

evaluation. If $n > t$, functions $f(n-1)$ and $f(n-2)$ are evaluated in parallel. Otherwise $f(n)$ is evaluated sequentially.

The Mandelbrot set is the set of points on the complex plane that remains bounded to the set when an iterative function is applied to that. It consists of all points defined by the complex elements c for which the recursive formula $z_{n+1} = z_n^2 + c$ does not approach infinity when $z_0 = 0$ and n approach infinity. A depth parameter is used to control the cost of sequential Mandelbrot computations. A higher depth gives more detail and subtlety in the final image representation of the Mandelbrot set [22].

The n-queens problem computes how many ways n queens can be put on an $n \times n$ chessboard so that no 2 queens attack each other [138]. The implementation uses divide-and-conqueror parallelism with an explicit threshold. An exhaustive search algorithm is used.

6.3.2 Measurement Methodologies

Nodes on both the Beowulf (Section 6.3.3) and HECToR (Section 6.3.3) have 8 cores, 7 of which are used by each HdpH-RS node instance to limit variability [78] [114]. For every data point, the mean of 5 runs are reported along with standard error. Standard error is the mean, calculated by dividing the population standard deviation by the square root of the sample size, as $SE_{\bar{x}} = \frac{s}{\sqrt{n}}$. The speedup in this chapter is measured by comparing the runtime of executing a skeleton on N cores with the execution of the same skeleton on 1 core. So if the mean runtime of `parMapSliced` on 1 core of 1 node is 500 seconds, and on 10 nodes i.e. 70 cores the mean runtime is 50 seconds then the speedup on 70 cores is 10.

6.3.3 Hardware Platforms

The HdpH-RS benchmarks are measured on two platforms. The first is a Beowulf cluster and is used to measure supervision overheads, and recovery latency in the presence of simultaneous and random failure. The second is HECToR, a national UK high-performance computing service. The failure rates for HECToR are described in Section 2.2.2, which shows that there were 166 single node failures between January 2012 to January 2013. The distributed programming models supported by HECToR all depend on MPI for node-to-node communication. Peer discovery with UDP is not supported, so the HdpH-RS fault detecting transport layer (Section 5.5) cannot be used. The MPI-based HdpH transport layer has been retrofitted in to HdpH-RS for the purposes of assessing the scalability of the supervised work stealing in HdpH-RS on HECToR in the absence of faults.

Beowulf Cluster

HdpH-RS is measured on a Heriot-Watt 32 node Beowulf cluster. Each Beowulf node comprises two Intel Xeon E5504 quad-core CPUs at 2GHz, sharing 12Gb of RAM. Nodes are connected via Gigabit Ethernet and run Linux CentOS 5.7 $x86\_64$. Benchmarks are run on up to 32 HdpH-RS nodes, scaling up to 256 cores.

HECToR Cluster

To measure scalability HdpH-RS is measured on a UK national compute resource. The HECToR compute hardware is contained in 30 cabinets and comprises a total of 704 compute blades. Each blade contains four compute nodes running Compute Node Linux, each with two 16 core AMD Opteron 2.3GHz Interlagos processors. This amounts to a total of 90,112 cores. Each 16-core socket is coupled with a Cray Gemini routing and communications chip. Each 16-core processor shares 16Gb of memory, giving a system total of 90.1Tb. The theoretical performance of HECToR is over 800 Teraflops. There are four HdpH-RS node instances launched on each host. The 32 cores on each host is separated in to four NUMA [190] regions. Each HdpH-RS node instance (i.e. GHC executable) is pinned to a specific 8 core NUMA region. Benchmarks are run on up to 200 HdpH-RS nodes. Each node uses 7 cores to reduce variability, so HdpH-RS benchmarks are scaled up to 1400 cores on HECToR.

6.4 Performance With No Failure

6.4.1 HdpH Scheduler Performance

The HdpH-RS shared-memory scheduling of sparks and threads is inherited from HdpH without modification. This section uses the Queens benchmark to measure shared-memory parallel performance. A `forkMap` skeleton has been added to HdpH by the author, and is used to compare shared-memory parallelism performance of HdpH against monad-par [118], on which the shared-memory HdpH scheduler is based. It also compares the overhead of sparks and supervised sparks using the `parMap` and `parMapFT` skeletons.

The monad-par Queens implementation [118] (Listing 6.8) uses a divide-and-conquer pattern with a parallel map to decompose tasks into subtasks. This implementation has been ported faithfully to HdpH using `forkMap`, `parMap` and `parMapFT`. The HdpH-RS test-suite also includes more abstract divide-and-conquer skeleton implementations (Section 6.5.2) that are not evaluated here.

The shared-memory performance is measured with a 16×16 Queens board, with

```
1  monadpar_queens :: Int → Int → MonadPar.Par [[Int]]
2  monadpar_queens nq threshold = step 0 []
3    where
4      step :: Int → [Int] → MonadPar.Par [[Int]]
5      step !n b
6          | n ≥ threshold = return (iterate (gen nq) [b] !! (nq - n))
7          | otherwise = do
8              rs ← MonadPar.C.parMapM (step (n+1)) (gen nq [b])
9              return (concat rs)
10
11     safe :: Int → Int → [Int] → Bool
12     safe _ _ []    = True
13     safe x d (q:l) = x /= q && x /= q + d && x /= q-d && safe x (d + 1) l
14
15     gen :: [[Int]] → [[Int]]
16     gen bs = [ q:b | b ← bs, q ← [1..nq], safe q 1 b ]
```

Listing 6.8: Queens Implementation using `monad-par`

thresholds from 1 to 6, increasing the number of generated tasks from 16 to 1002778. The monad-par executions bypasses the HdpH scheduler completely, and instead uses its own scheduler. All runs are given 7 processing elements from GHC with the `+RTS -N7` runtime option.

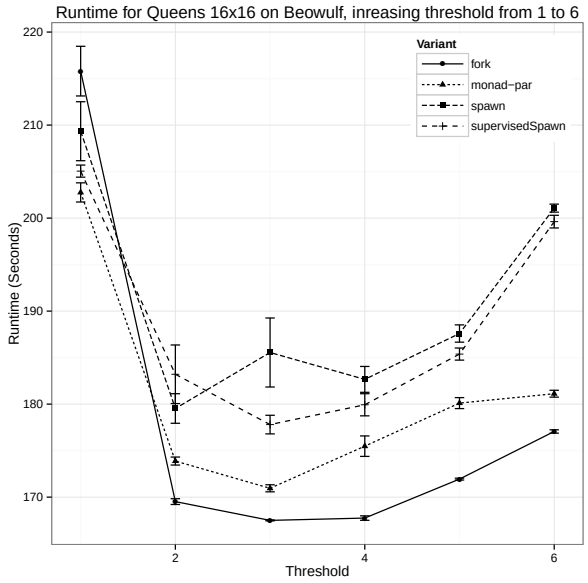


Figure 6.1: Runtimes for 16×16 Queens Board Comparing HdpH and monad-par on 7 cores

Figure 6.1 shows the mean of five runs for all implementations with a standard error bar at each threshold. All implementations have a similar runtime performance. The mean runtime with a threshold of 1 yields the slowest runtimes in all cases. Optimal

runtimes are observed when the threshold is between 2 and 4. All runtimes increase in tandem with a threshold increase from 4 to 6. Variability of the 5 runtimes for all runs with HdpH-RS's `spawn` and `supervisedSpawn` is higher than `fork` in HdpH or monad-par's `spawn`. The standard error is smaller as the threshold increases from 3 to 6 for all cases. That is, variability diminishes as the number of generated tasks increases, reducing granularity.

The `fork` implementation using HdpH achieves lower runtimes than monad-par for all threshold values except 1. This is somewhat surprising, though the difference is not great. It suggests that there is no performance penalty in opting for the HdpH-RS scheduler versus the shared-memory-only monad-par scheduler, if HdpH-RS threads are used.

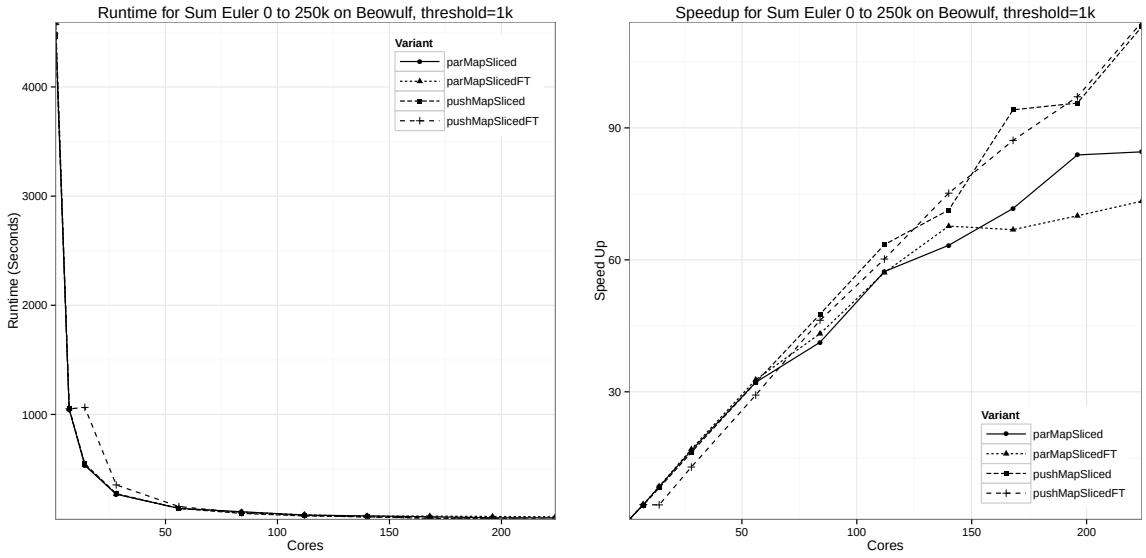
The HdpH-RS runtimes using `spawn` or `supervisedSpawn` are slower than using `fork`. This runtime gap widens as the threshold increases to 5 and 6, generating 163962 and 1002778 sparks respectively. The increase may be attributed to two aspects of the architecture. First, there may be contention on the node-global sparkpool data structure, which is implemented as a double ended pure data structure in an `IORef` and is atomically locked as sparks are added and removed. Second, the evaluation of values during modifications to the `IVar` registry may not be sufficiently strict. The registry is not used by the `fork` primitive.

6.4.2 Runtime & Speed Up

Sum Euler

The speedup performance of Sum Euler is measured on the Beowulf cluster up to 224 using $[1, 2, 4, 8..32]$ nodes with $X = 250k$ and a threshold of $1k$. The runtimes are shown in Figure 6.2a and the speedup in Figure 6.2b. Lazy scheduling is assessed with `parMapSliced` and `parMapSlicedFT`. Eager scheduling is assessed using `pushMapSliced` and `pushMapSlicedFT`.

The speedup results for Sum Euler are in Figure 6.2b. The speedup results show that the two eager skeletons scale better than the two lazy scheduling skeletons for Sum Euler. At 224 cores using 32 nodes the `pushMapSliced` and `pushMapSlicedFT` mean runtimes are 39.5s and 40.1s respectively, speedup's of 113 and 114. The `parMapSliced` and `parMapSlicedFT` mean runtimes are 53.1s and 67.9s respectively, speedup's of 84.6 and 67.5. The eager skeletons achieve quicker runtimes because task regularity is fairly consistent due to input slicing. The slight speedup degradation after 56 cores when using lazy work stealing is likely due to the latency of lazy work stealing.



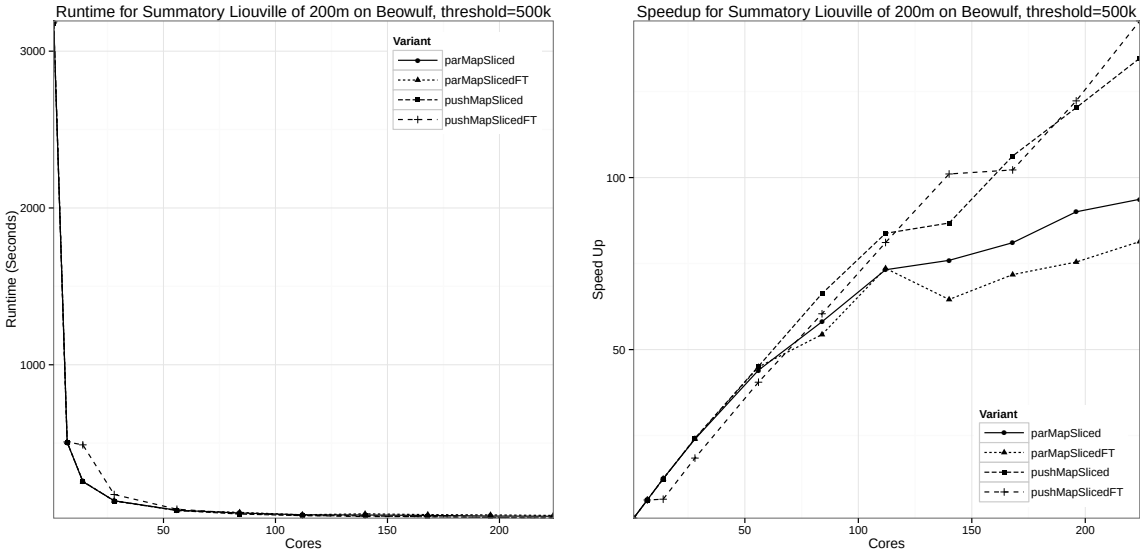
(a) Runtime (b) Speedup

Figure 6.2: Sum Euler on Beowulf

Summatory Liouville

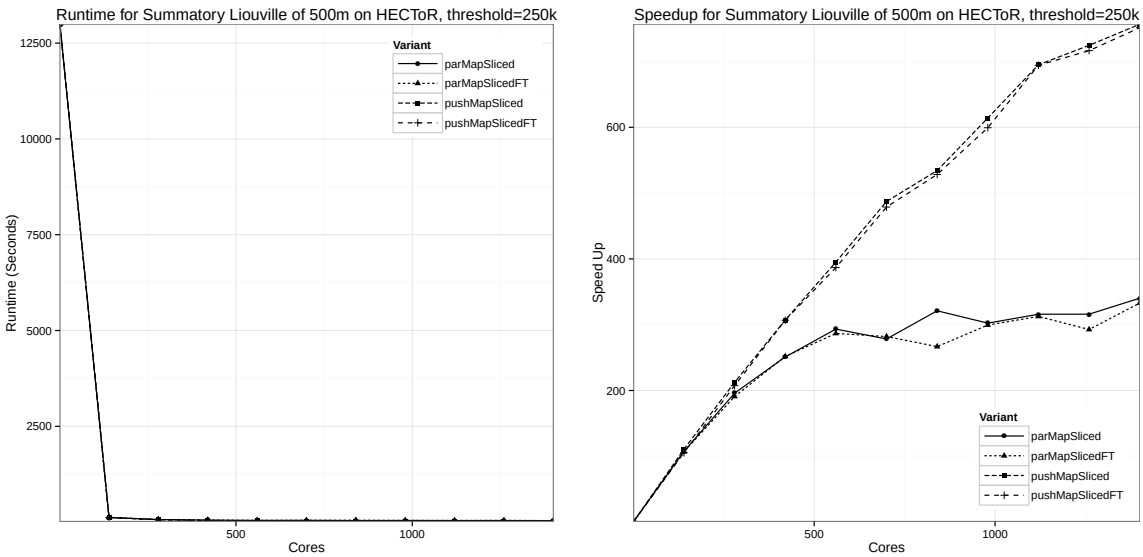
The speedup performance of Summatory Liouville is measured on the Beowulf cluster up to 224 cores using $[1, 2, 4, 8..32]$ nodes with $n = 200m$ and a threshold of $500k$. It is also measured on the HECToR cluster up to 1400 cores using $[20, 40..200]$ nodes with $n = 500m$ and a threshold of $250k$. On HECToR, the n value is larger and the threshold smaller than Beowulf as more tasks need to be generated to fully utilise the architecture. That is, 2000 tasks for the 1400 cores on HECToR and 400 tasks for the 244 cores on Beowulf. The Beowulf runtimes are shown in Figure 6.3a and the speedup in Figure 6.3b. The HECToR runtimes are shown in Figure 6.4a and the speedup in Figure 6.4b. Once again, lazy scheduling is assessed with `parMapSliced` and `parMapSlicedFT`. Eager scheduling is assessed with Sum Euler implementations using `pushMapSliced` and `pushMapSlicedFT`.

The same trend emerges as observed measuring Sum Euler, when comparing lazy and eager skeletons. That is, due the task regularity achieved using input slicing, eager scheduling outperforms lazy scheduling at larger scales. The latency of work stealing impacts on speedup for the two lazy skeletons after 56 cores on Beowulf, and after 280 cores on HECToR. All four skeletons continue to speedup as cores are increased on both Beowulf and HECToR. The speedup of the eager skeletons at 224 cores on Beowulf is 134.7 and 145.5 and at 1400 cores on HECToR is 751.4 and 756.7. The speedup of the lazy skeletons at 224 cores on Beowulf is 81.4 and 93.7 and at 1400 cores on HECToR is 332.9 and 340.3.



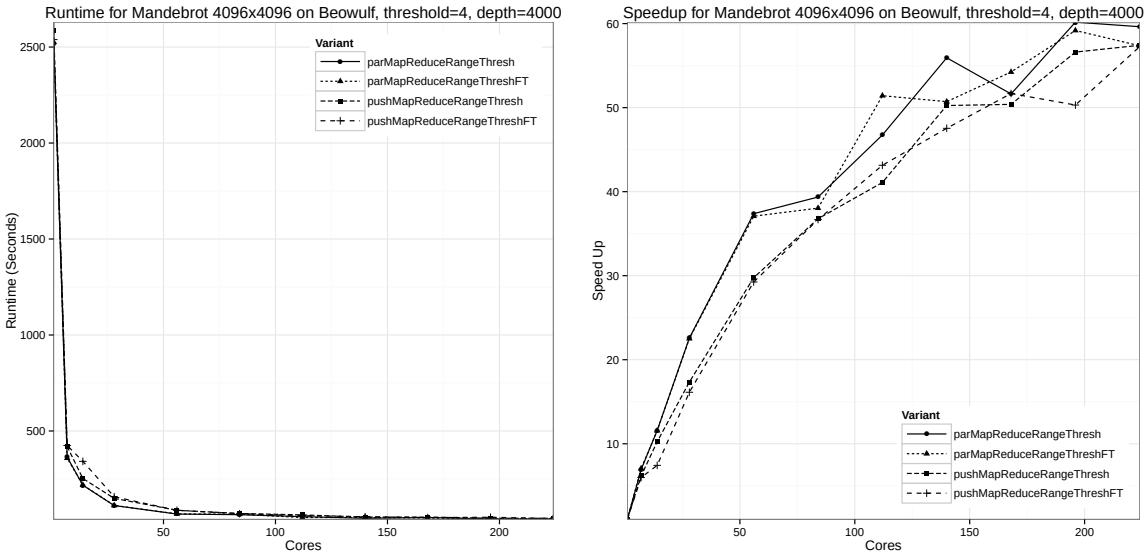
(a) Runtime (b) Speedup

Figure 6.3: Summatory Liouville on Beowulf



(a) Runtime (b) Speedup

Figure 6.4: Summatory Liouville on HECToR



(a) Runtime (b) Speedup

Figure 6.5: Mandelbrot on Beowulf

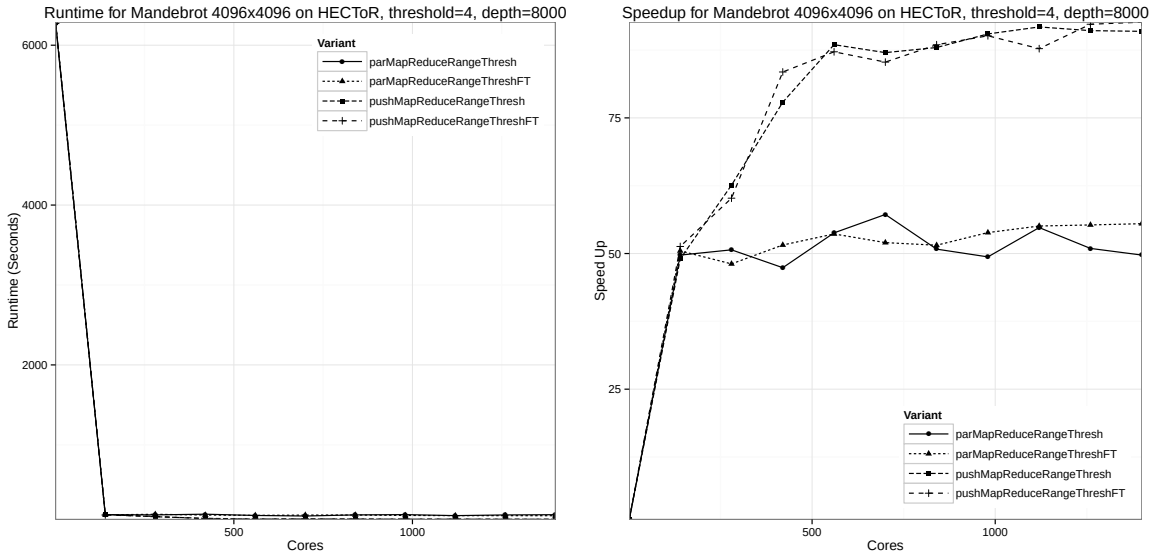
The supervision overhead costs for Summatory Liouville are marginal at all scales on both Beowulf and HECToR. The overheads are negligible on the HECToR HPC architecture (Figure 6.4b) demonstrating that the supervision in HdpH-RS scales to large parallel architectures for regular task parallelism.

Mandelbrot

The speedup performance of Mandelbrot is measured on the Beowulf cluster using $[1, 2, 4, 8..32]$ nodes with $X = 4096$, and $Y = 4096$, a threshold of 4 controlling the number of tasks, which is 1023 in this case. The depth is 4000. It is also measured on the HECToR cluster using $[20, 40..200]$ nodes with $X = 8192$, and $Y = 8192$, a threshold of 4 controlling the number of tasks, which is 1023 in this case. The depth is 8000. The Beowulf runtimes are shown in Figure 6.5a and the speedup in Figure 6.5b. The HECToR runtimes are shown in Figure 6.6a and the speedup in Figure 6.6b.

The Beowulf runtimes in Figure 6.5b shows that all four skeletons speedup with only slight degradation up to 244 cores. There is no clear distinction between the lazy and eager skeletons, and the supervision costs of the fault tolerant skeletons are neglible. The speedup of all four skeletons peaks at either 196 or 224 cores — between 57.4 and 60.2.

A contrast between lazy and eager scheduling is apparent in the HECToR speedup measurements in Figure 6.6b. Runtimes are improved for the eager skeletons continue up to 560 cores, with speedup's of 87.2 and 88.5. A modest speedup from 560 to 1400 cores is observed. The lazy skeletons no longer exhibit significant speedup after 140 cores, hitting



(a) Runtime (b) Speedup

Figure 6.6: Mandelbrot on HECToR

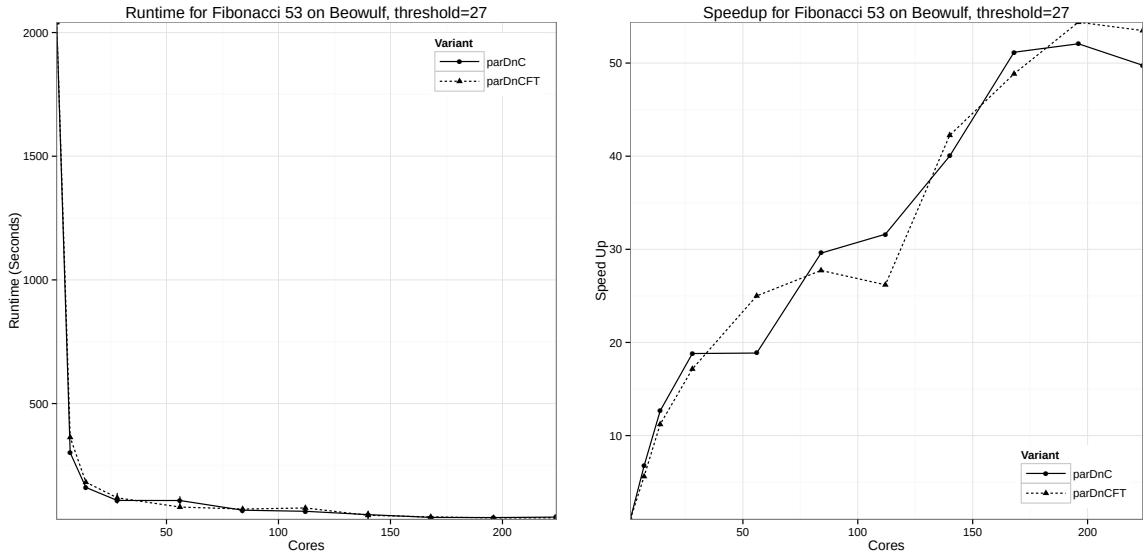
speedup's of 49.7 and 50.5. Thereafter, speedup relative to using 1 core is constant up to 1400 cores, with `parMapReduceRangeThresh` peaking at 57.2 using 700 cores.

The supervision overhead costs for Mandelbrot are marginal at all scales on both Beowulf and HECToR. The overheads are negligible on the HECToR HPC architecture (Figure 6.6b) demonstrating that the supervision in HdpH-RS scales to large parallel architectures for divide-and-conquer style parallelism with hierarchically nested supervision.

Fibonacci

The speedup performance of Fibonacci is measured on the Beowulf cluster up to 224 cores using $[1, 2, 4, 8..32]$ nodes with $X = 53$ and a threshold of 27. Lazy task placement is measured with `parDnC`, a divide-and-conquer skeleton with lazy scheduling. Fault tolerant lazy task placement is measured with `parDnCFT`. Explicit skeletons `pushDnC` and `pushDnCFT` were tried with Fibonacci 53 with the threshold 27. Whilst the mean runtimes for `parDnC` and `parDnCFT` using 7 cores is 301.4 and 363.6 seconds, the `pushDnC` and `pushDnCFT` implementations run for 1598.2 and 1603.3 seconds respectively. Scaling to more nodes only increased runtimes with explicit scheduling e.g. a mean runtime of 2466.0 seconds for `pushDnC` using 14 cores. Only results with lazy scheduling are plotted. The runtimes are shown in Figure 6.7a and the speedup in Figure 6.7b.

Fibonacci was implemented using the lazy divide-and-conquer skeletons. The runtimes for `parDnCFT` are very similar to `parDnC` at all scales, demonstrating that hierarchically



(a) Runtime (b) Speedup

Figure 6.7: Fibonacci on Beowulf

nested supervision costs are negligible. The speedup of both the fault tolerant and non-fault tolerant skeletons peak at 196 core on Beowulf, at 54.4 and 52.1 respectively.

6.5 Performance With Recovery

6.5.1 Simultaneous Multiple Failures

The HdpH-RS scheduler is designed to survive simultaneous failure. These can occur for many reasons e.g. due to network or power supply hardware failures to partitions of a cluster. Node failure recovery is distributed, the failure of a node will eventually be detected by all healthy nodes. Each is responsible for taking recovery action. That is, a node must replicate tasks corresponding to supervised futures that it hosts, in accordance with Algorithm 10 from Section 3.5.4.

This section uses the `killAt` poisonous RTS flag to instruct the root node to poison 5 nodes, i.e. 35 cores simultaneously at a set time. The experiment inputs in this section are set so that failure-free runtime is a little more than 60 seconds on 20 nodes. The 5 nodes are scheduled to die at [10,20..60] seconds in to the execution. The runtimes are compared to failure-free runs using the non-fault tolerant counterpart to assess recovery times.

Two benchmarks are used to measure recovery overheads, Summatory Liouville for task parallelism and Mandelbrot for divide-and-conquer parallelism. Summatory Liouville is a benchmark that is implemented with the parallel-map family. All tasks are generated

by the root node, and tasks are not recursively decomposed. The Mandelbrot benchmark is implemented with the map-reduce-thresh family, a divide-and-conquer pattern that results in the supervision of futures across multiple nodes.

Summatory Liouville

The inputs for Summatory Liouville are $n = 140m$, and a threshold of $2m$. This generates 70 tasks. The mean of 5 runs with `parMapSliced` is 66.8 seconds. The mean of 5 runs with `pushMapSliced` is 42.8 seconds.

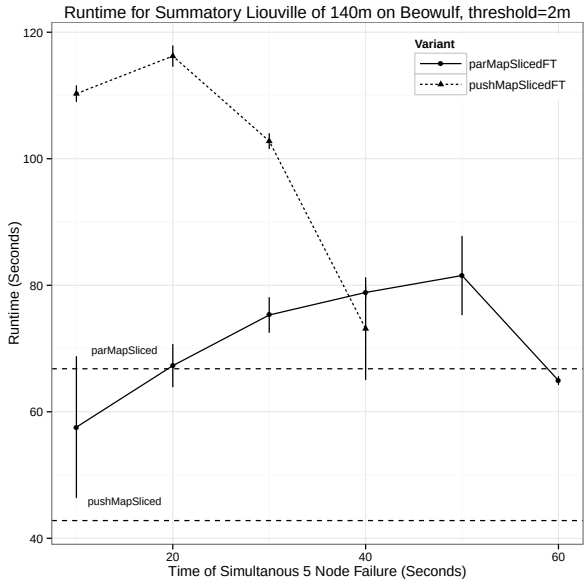


Figure 6.8: Simultaneous Failure of 5 Nodes Executing Summatory Liouville on Beowulf

The recovery from the death of 5 nodes at 6 different timings for Summatory Liouville is shown in Figure 6.8. The recovery overheads of lazy and eager scheduling follow different trends. All supervised futures are created on the root node in both cases of `parMapSlicedFT` and `pushMapSlicedFT`.

When eager scheduling is used, the recovery overheads are more substantial early on i.e. at 10, 20 and 30 seconds. These overheads compared with fault-free execution with `pushMapSlicedFT` are 158%, 172% and 140% respectively. As more tasks are evaluated and therefore more supervised futures on the root node filled, the recovery costs reduce at 60 seconds. At 40 seconds, the overhead is 70%. There are no measurements taken at 50 and 60 seconds as the mean failure-free runtime with `pushMapSliced` is 43 seconds, so the 5 node poison at 50 and 60 seconds would have no effect.

The recovery overheads for lazy scheduling with `parMapSlicedFT` follow an altogether different pattern. With a high standard error over the 5 executions with failure at 10 seconds, the mean runtime is *shorter* than failure-free execution with `parMapSliced` by

14%. Unlike eager task placement, this is likely due to a much smaller number of the 70 generated sparks being fished by the 5 nodes that had failed after only 10 seconds. Moreover, it is likely that the balance between computation and communication for the job size with $n = 140m$ favours smaller cluster than 20 nodes, i.e. the 15 nodes that are left. As the delay until failure is increased to 20, 30, 40 and 50 seconds, the recovery overheads are 2%, 13%, 18% and 22%. As most supervised futures on the root node become full at the 60 second failure executions, fewer sparks need replicating. Thus, the runtimes with failure at 60 seconds are close to the failure-free runtimes, resulting in a small speedup of 3%.

Mandelbrot

The inputs for Mandelbrot are $X = 4096$, $Y = 4096$, $threshold = 4$ and $depth = 4000$. This generates 1023 tasks. The mean of 5 runs with `parMapReduceRangeThresh` is 66 seconds. The mean of 5 runs with `pushMapReduceRangeThresh` is 92 seconds.

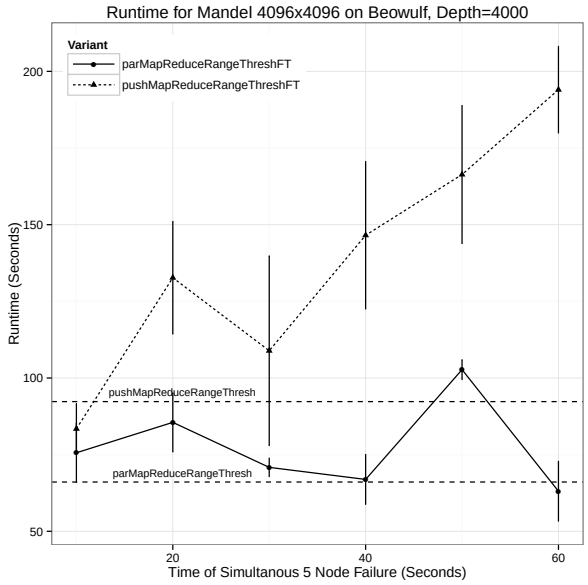


Figure 6.9: Simultaneous Failure of 5 Nodes Executing Mandelbrot on Beowulf

The recovery from the death of 5 nodes at the 6 different timings for Mandelbrot is shown in Figure 6.9, and reveals two distinct trends. The recovery overheads for the lazy `parMapReduceRangeThreshFT` skeleton are low, even as the number of generated supervised futures increases. The mean runtime when 5 nodes are killed at 60 seconds is marginally shorter by 3.0 seconds than failure-free execution with 20 nodes, a speedup of 5%.

The recovery overheads for the eager `pushMapReduceRangeThreshFT` skeleton increases as more threads are replicated needlessly (Section 6.5.3). Early failures of 10

seconds shortens runtime by 10%. The eventual total of 1023 threads will likely not have been created by this point, and balance between communication and computation for the inputs of $X = 4096$ and $Y = 4096$ may favour the smaller 15 node cluster size. However, when the 5 node failure occurs at 20, 30, 40, 50 and 60 seconds, the recovery costs increase. For these times, the recovery overheads are 44%, 18%, 59%, 80% and 110%.

6.5.2 Chaos Monkey

A unit testing suite is built-in to eight benchmarks (Table 6.5) to check that results computed by HdpH-RS in the presence of random failure are correct. Sum Euler is used to measure recovery costs of `parMapChunkedFT` and `pushMapChunkedFT`, Summatory Liouville to asses `parMapSlicedFT` and `pushMapSlicedFT`, Queens to measure `parDnCFT` and `pushDnCFT` and Mandelbrot to assess `parMapReduceRangeThreshFT` and `pushMapReduceRangeThreshFT`. The unit tests are invoked when the `chaosMonkey` flag is used. The chaos monkey failure injection exploits the UDP peer discovery in HdpH-RS, and is shown in Listing 6.9. The `chaosMonkeyPoison` function on line 8 is executed by the root node. It randomly decides how many of the non-root nodes will be poisoned (line 10), and the timing of failure in each case (line 11). These messages are sent to a randomly sorted node sequence.

The executing code on non-root nodes is `run` on line 19. A non-root node waits for a `Booted` message on line 21. If a `Booted Nothing` message is received then it is ignored. If a `Booted (Just x)` message is received, then a suicidal thread is forked on line 24. It will kill the node at x seconds in to the job execution.

The `HUnit` test framework [80] is used in the HdpH-RS function `chaosMonkeyUnitTest` shown in Listing 6.10 and verifies that the fault tolerant skeletons return the correct result with chaos monkey enabled. For example, the `chaosMonkeyUnitTest` takes a HdpH-RS RTS configuration, a `String` label for the test e.g. "sumeuler-0-50k-chaos-monkey", then an expected value 759924264 for a parallel Sum Euler 0 to 50000 computation in the `Par` monad. The implementation of `chaosMonkeyUnitTest` is in Appendix A.10.

An execution of Sum Euler with the fault tolerant `pushMapChunkedFT` skeleton is shown in Listing 6.11. It asks for 5 node instances from `mpiexec` with the `-N 5` flag, and HdpH-RS is told discover 5 nodes via UDP with `-numProcs=5`. MPI is forced to ignore a node failure with the `--disable-auto-cleanup` flag. The `chaosMonkey` flag turns on random node failure. The root node non-deterministically decides that 3 nodes shall fail. The first will fail at 4 seconds, the second at 23 seconds and the third at 36 seconds. When failure is detected, the at-risk threads on the failed node are re-scheduled. There are no sparks to re-schedule because `pushMapChunkedFT` is entirely explicit, using

```
1  -- | Executed on root node when -chaosMonkey flag is used.
2  --      Give a (< 60 second) poison pill to random number of nodes:
3  --        (Booted Nothing) means remote node is not poisoned.
4  --        (Booted (Just x)) means remote node dies after x seconds.
5  --
6  --      If -chaosMonkey flag is not used, this function is not used.
7  --      Instead, every non-root node is sent (Booted Nothing) message.
8  chaosMonkeyPoison :: [NodeId] → IO [(NodeId,Msg)]
9  chaosMonkeyPoison nodes = do
10   x ← randomRIO (0,length nodes) -- number of nodes to poison
11   deathTimes ← take x ∘ randomRs (0,60) <$> newStdGen -- nodes die within 60 seconds
12   randNodes ← shuffle nodes
13   let pills =    map (Booted ∘ Just) deathTimes  -- poison pills
14               ++ repeat (Booted Nothing)        -- placebo pills
15   return (zip randNodes pills)
16
17 -- | Executed on non-root nodes:
18 --      node waits for 'Booted _' message in 'Control.Parallel.HdpH.Internal.Comm'
19 run = do
20     {- omitted UDP discovery code -}
21     (Booted x) ← waitForRootNodeBootMsg -- receive bootstrap from root
22     -- fork a delayed suicide if (Boot (Just x)) received
23     when (isJust x) $ void $ forkIO $ do
24         threadDelay (1000000 * fromJust x) » raiseSignal killProcess
25     {- omitted transport layer initialisation -}
```

Listing 6.9: Implementation of Chaos Monkey

```
1  chaosMonkeyUnitTest
2        :: (Eq a)
3        ⇒ RTSConf -- user defined RTS configuration
4        → String  -- label identifier for unit test
5        → a       -- expected value
6        → Par a   -- Par computation to execute with failure
7        → IO ()
```

Listing 6.10: API for Chaos Monkey Unit Testing

`supervisedSpawnAt`. Intuitively as time progresses, fewer threads will need re-scheduling, as more `IVar`s are filled by executing threads. Hence, 26 threads are re-scheduled after the 4 second failure, 20 threads after the 23 second failure, and 17 threads after the 36 second failure. The last line in 6.11 indicates that the execution terminated and the result was matched to the correct result 759924264.

Listing 6.11: Execution of Sum Euler with `pushMapFT` & Chaos Monkey Fault Injection

```
$ mpiexec -N 5 --disable-auto-cleanup sumeuler -numProcs=5 -chaosMonkey v13
Chaos monkey deaths at (seconds): [4,23,36]
kamikaze 137.195.143.115:31250:0
```

```
replicating threads: 26
kamikaze 137.195.143.115:31631:0
replicating threads: 20
kamikaze 137.195.143.115:29211:0
replicating threads: 17
sumeuler-pushMapChunkedFT result: 759924264
Cases: 1  Tried: 1  Errors: 0  Failures: 0
```

An execution of Sum Euler with the fault tolerant `parMapChunkedFT` skeleton is shown in Listing 6.12. Again 5 nodes are used, with chaos monkey poisoning 4 of them, to die at 6, 7, 35 and 55 seconds. Fewer replications are re-scheduled i.e. 3× 2 replicas and 1× 1 replica, due to lazy work stealing of sparks in contrast to preemptive eager round-robin task placement with `pushMapChunkedFT`. The last line in 6.12 indicates that the execution terminated and the result was matched to the correct result 759924264.

Listing 6.12: Execution of Sum Euler with `parMapFT` & Chaos Monkey Fault Injection

```
$ mpiexec -N 5 --disable-auto-cleanup sumeuler -numProcs=5 -chaosMonkey v10
Chaos monkey deaths at (seconds): [6,7,35,55]
kamikaze 137.195.143.125:18275:0
replicating sparks: 2
kamikaze 137.195.143.125:15723:0
replicating sparks: 1
kamikaze 137.195.143.125:31678:0
replicating sparks: 2
kamikaze 137.195.143.125:31216:0
replicating sparks: 2
sumeuler-parMapChunkedFT result: 759924264
Cases: 1  Tried: 1  Errors: 0  Failures: 0
```

Chaos Monkey Results

The results of chaos monkey unit testing is shown in Table 6.5. All experiments were launched on 10 nodes of the Beowulf cluster. The *Benchmarks* column shows the input, threshold, number of generated tasks, and expected values for each benchmark. The *Skeleton* column states which fault tolerant parallel skeleton is used to parallelise the implementation. The *Failed Nodes* column shows a list of integers. The length of this list indicates the number of nodes that were poisoned with chaos monkey. The integer values indicate the time in seconds at which a node will fail. For example the list `[24,45]` states that two nodes will fail, the first at 24 seconds and the second at 45 seconds. The *Recovery* column states how many tasks were recovered across all remaining nodes to recover from failure throughout execution. For the implicit skeletons e.g. `parMapFT` only

sparks are generated and thus recovered. For the implicit skeletons e.g. `pushMapFT` only threads are generated and recovered. The *Runtime* column shows the runtime for each execution. Lastly, the *Unit Test* column states whether the result from HdpH-RS in the presence of failure matched the pre-computed result using HdpH with no failure. The test-suite passes 100% of the unit tests.

The key observation from these results is that lazy scheduling reduces recovery costs in the presence of failure. The `parDnCFT` skeleton (divide-and-conquer using `supervisedSpawn`) creates only sparks, initially on the root node, which get fished away with work stealing. The `pushDnCFT` skeleton uses `supervisedSpawnAt` to randomly select nodes to eagerly scheduled tasks as threads. The laziness of `supervisedSpawn` minimises the migration of sparks, taking place only when nodes become idle. It also minimises the number of sparks that need to be recovered. For example, the Queens unit test generates 65234 tasks. The `pushDnCFT` results in the re-scheduling of 40696 threads in the case of between 1 and 3 node failures at $[3, 15, 15]$ before the execution would have likely terminated at 15 seconds. Subsequent node failures at $[23, 24, 28, 32, 48]$ seconds may have resulted in multiple replicas of tasks being eagerly scheduled as earlier scheduled replicas may have also been lost. The runtime to termination is 650 seconds. The Queens unit test with `parDnCFT` results in the re-scheduling of only 8 sparks in another case of 5 likely node failures at $[3, 8, 9, 10, 17]$ before the execution would have likely terminated at 28 seconds. Subsequent node failures at $[45, 49, 51]$ seconds may have resulted in multiple replicas of tasks being lazily scheduled as earlier scheduled replicas may have also been lost. The runtime to termination is 52 seconds. An explanation for the much lower impact of failure when on-demand work stealing is used is given in Section 6.5.3.

On-demand work stealing also manages the trade off between communication and computation by reducing unnecessary task scheduling to remote nodes if task granularity is very small. The Mandelbrot benchmark is used to demonstrate this. The depth is set at 256, a relatively low number that generates small task sizes (the speed-up is later measured in Section 6.4.2 using a depth of 4000). The small Mandelbrot task sizes in the chaos monkey experiments mean that very few sparks are replicated as most are executed by the root node. In 3 runs, 0 sparks are replicated including an execution with 8 node failures. In contrast, 686 threads are replicated with a failure accumulation of 8 nodes, when eager scheduling pushes tasks to remote nodes regardless of task size.

6.5.3 Increasing Recovery Overheads with Eager Scheduling

The lazy task scheduling with `parMapChunkedFT` for Sum Euler, `parMapSlicedFT` for Summatory Liouville, `parDnCFT` for Queens, and `parMapReduceFT` for Mandelbrot result

Table 6.5: Fault Tolerance Unit Testing: Chaos Monkey Runtimes

Benchmark	Skeleton	Failed Nodes (seconds)	Recovery		Runtime (seconds)	Unit Test
			Sparks	Threads		
Sum Euler *lower=0 upper=100000 chunk=100 tasks=1001 X=3039650754*	`parMapChunked`	-			126.1	pass
	`parMapChunkedFT`	[6,30,39,49,50]	10		181.1	pass
		[5,11,18,27,28,33,44,60]	16		410.2	pass
		[31,36,49]	6		139.7	pass
		[37,48,59]	6		139.5	pass
		[1,17,24,27,43,44,47,48,48]	17		768.2	pass
	`pushMapChunked`	-			131.6	pass
	`pushMapChunkedFT`	[4,34,36,37,48,49,58]		661	753.7	pass
		[2,6,11,15,17,24,32,37,41]		915	1179.7	pass
		[2,37,39,45,49]		481	564.0	pass
		[4,7,23,32,34,46,54,60]		760	978.1	pass
		[35,38,41,43,46,51]		548	634.3	pass
Summatory Liouville $\lambda = 50000000$ *chunk=100000 tasks=500 X=-7608*	`parMapSliced`	-			56.6	pass
	`parMapSlicedFT`	[32,37,44,46,48,50,52,57]	16		85.1	pass
		[18,27,41]	6		61.6	pass
		[19,30,39,41,54,59,59]	14		76.2	pass
		[8,11]	4		62.8	pass
		[8,9,24,28,32,34,40,57]	16		132.7	pass
	`pushMapSliced`	-			58.3	pass
	`pushMapSlicedFT`	[3,8,8,12,22,26,26,29,55]		268	287.1	pass
		[1]		53	63.3	pass
		[10,59]		41	68.5	pass
		[13,15,18,51]		106	125.0	pass
		[13,24,42,51]		80	105.9	pass
Queens 14×14 *board threshold=5 tasks=65234 X=365596*	`parDnC`	-			28.1	pass
	`parDnCFT`	[3,8,9,10,17,45,49,51,57]	8		52.1	pass
		[1,30,32,33,48,50]	5		49.4	pass
		[8,15]	2		53.3	pass
		[20,40,56]	2		49.9	pass
		[]	0		52.8	pass
	`pushDnC`	-			15.4	pass
	`pushDnCFT`	[14,33]		5095	57.1	pass
		[3,15,15,23,24,28,32,48]		40696	649.5	pass
		[5,8,26,41,42,42,59]		36305	354.9	pass
		[0,5,8,10,14,28,31,51,54]		32629	276.9	pass
		[31,31,58,60]		113	47.8	pass
Mandelbrot *x=4048 y=4048 depth=256 threshold=4 tasks=1023 X=449545051*	`parMapReduceRangeThresh`	-			23.2	pass
	`parMapReduceRangeThreshFT`	[28,30,36,44,49,54,56,56]	0		29.1	pass
		[]	0		27.8	pass
		[7,24,25,25,44,53,54,59]	6		32.6	pass
		[17,30]	0		55.4	pass
		[0,14]	2		33.7	pass
	`pushMapReduceRangeThresh`	-			366.3	pass
	`pushMapReduceRangeThreshFT`	[9,24,34,34,52,59]		419	205.3	pass
		[7,8,11,22,32,35,44,46]		686	395.9	pass
		[27,49]		2	371.8	pass
		[]		0	380.4	pass
		[9,33,50,50,52,53]		84	216.1	pass

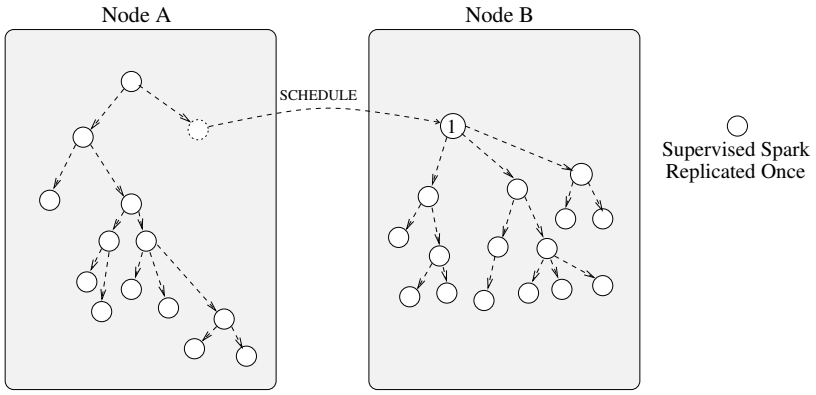


Figure 6.10: Isolated Supervision Trees with Lazy Scheduling

in lower recovery costs than their eager skeleton counterparts. For example, the Chaos Monkey data for Sum Euler in Table 6.5 show that the number of replicated sparks with `parMapChunkedFT` is between 6 and 17, with a runtime minimum of 140s and maximum of 768s. The number of replicated threads with `pushMapChunkedFT` is between 481 and 915, with a runtime minimum of 564s and a maximum of 1180s.

In the eager divide-and-conquer cases of Queens and Mandelbrot, most threads are unnecessarily re-scheduled. This is illustrated in Figures 6.10 and 6.11. A simple example of lazy scheduling is shown in Figure 6.10. The root node A initially decomposes the top function call in to 2 separate sparks. One is fished away to node B. The recursive decomposition of this task saturates node B with work, and it no longer fishes for other sparks. If node B fails, node A lazily re-schedules a replica of only the top level spark.

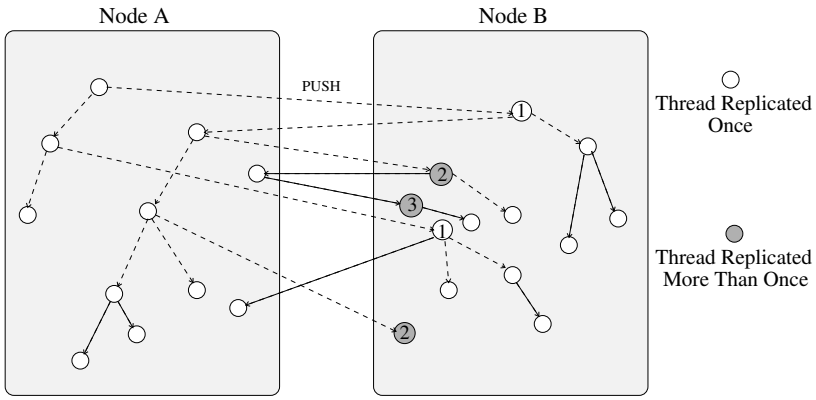


Figure 6.11: Split Supervision Trees with Eager Scheduling

The reason for the high level of thread rescheduling for all benchmarks (Table 6.5) is illustrated in Figure 6.11. As before, node A decomposes the top level function call in to 2 separate tasks. With random work distribution, one is pushed eagerly to node B. Converting and executing this task generates 2 more child tasks, one being pushed back to A. This happens for a 3rd time i.e. a supervision tree is split between nodes A and

B. The failure of node B will result in the necessary replication of the top level task on B, and the unnecessary replication of the grey tasks on B. The supervision tree will be regenerated, thus replicating these grey children for a 2nd and 3rd time respectively.

The pattern of results for Sum Euler are mirrored in the Summatory Liouville, Queens and Mandelbrot runtimes. That is, lazy scheduling results in much lower replica numbers and hence shorter runtimes in the presence of failure. There are some cases where failure costs are very low, even when with a high failure rate. There are 2 runs of Sum Euler that incurs 3 node failures, of the 10 nodes used at the start. Their runtimes are both 139s, in comparison to fault-free execution with `parMap` of 126.1s — an increase of 11%. An execution of Summatory Liouville incurs the failure of 7 nodes. The runtime is 76s, an increase of 35% in comparison to fault-free execution on 10 nodes. This increase is attributed to failure detection latency, the recovery of 14 sparks, and a decrease in compute power of 30% i.e. 3 out of 10 nodes. There are examples when the timing of failure is larger than the execution time. For example, chaos monkey schedules 8 node failures for one run of Mandelbrot. However, the execution is complete after 29s, so only one node will have failed by then, after 28 seconds.

The large recovery costs of using eager skeletons is due in-part to their naive design. The HdpH-RS skeletons `pushMapFT`, `pushMapSlicedFT`, `pushMapChunkedFT`, `pushDnCFT` and `pushMapReduceRangeThreshFT` are built on top of the HdpH-RS `supervisedSpawnAt` primitive. Task placement at all levels of the supervision tree is random. It does not consider the location of parent supervisors, or organise nodes as tree structures corresponding to the supervision tree. These techniques could avoid unnecessary replication and is left as future work.

6.6 Evaluation Discussion

This chapter has shown how to write fault tolerant programs with HdpH-RS, and has evaluated the performance of HdpH-RS in the absence and presence of faults. The speedup results demonstrate that when task size variability can be lowered with input slicing, eager preemptive scheduling achieves shorter runtimes than lazy scheduling with work stealing. However when failures are present, on-demand lazy scheduling is more suitable for minimising recovery costs. Recovery costs of lazy scheduling is low even when failure frequency is high e.g. 80% node failure. The supervision costs incurred by using the fault tolerant fishing protocol is negligible on the Beowulf cluster and on HECToR, demonstrating that the HdpH-RS scheduler can be scaled to massively parallel architectures.

Two benchmarks were used to assess the performance of single level supervision with

parallel-map skeletons and three were used to assess hierarchically nested supervision with map-reduce and divide-and-conquer skeletons. These were executed on 244 cores of a 32 node Beowulf cluster, and 1400 cores on HECToR.

The Sum Euler and Summatory Liouville benchmarks were implemented with lazy and eager parallel-map skeletons and input slicing was used to regulate task sizes. This flattening of task sizes diminished the need for lazy work stealing. As a result, the fault tolerant eager scheduling achieved better speedup's at scale. A speedup of 114 was achieved using explicit scheduling of Sum Euler executed on Beowulf using 224 cores, and 68 with lazy scheduling. A speedup of 146 was achieved using explicit scheduling of Summatory Liouville, and 94 with lazy scheduling. A speedup of 757 was achieved using explicit scheduling of Summatory Liouville on HECToR using 1400 cores, and 340 with lazy scheduling.

The Mandelbrot benchmark is implemented with lazy and eager map-reduce skeletons. There is no clear distinction between the lazy and eager skeletons executed on Beowulf. The speedup of all four skeletons peaks at either 196 or 224 cores — between 57.4 and 60.2. A contrast between lazy and eager scheduling is apparent in the HECToR speedup measurements. Runtimes improve for the eager skeletons, continuing up to 560 cores with a speedup of 88.5. A modest speedup from 560 to 1400 cores is observed thereafter. The lazy skeleton no longer exhibits significant speedup after 140 cores, peaking with a speedup of 50.5.

Fibonacci was implemented using the lazy divide-and-conquer skeletons. The runtimes for `parDnCFT` and very similar to `parDnC` at all scales. As with Mandelbrot, Fibonacci demonstrates that hierarchically nested supervision costs are negligible. The speedup of both the fault tolerant and non-fault tolerant skeletons peak at 196 core on Beowulf, at 54.4 and 52.1 respectively.

Four benchmarks are used to assess the resiliency of the parallel-map, map-reduce and divide-and-conquer skeletons in the presence of randomised Chaos Monkey failure. The executions with fault occurrence were executed on Beowulf — a platform that, unlike HECToR, supports the UDP peer discovery in the fault detecting TCP-based HdpH-RS transport layer. The key observation from these results is that lazy scheduling reduces recovery costs in the presence of frequent failure. Lazy skeletons generate sparks that are only scheduled elsewhere if requested through on-demand work stealing. This laziness minimises the migration of sparks, taking place only when nodes become idle. Eager skeletons preemptively distribute work from the task generating nodes, regardless of work load of other nodes. Lazy scheduling therefore minimises the number of tasks that need to be recovered when failures are detected.

For example, the Queens unit test generates 65234 tasks. Using the eager `pushDnCFT` skeleton results in the re-scheduling of 40696 threads in an execution during which 8 of the initial 10 nodes fail. This leads to an increased runtime of 649 seconds compared to the mean 15 seconds of 5 failure-free `pushDnC` runtimes. In contrast, an execution using the lazy `parDnCFT` skeleton in the presence of 9 node failures results in the re-scheduling of only 8 sparks. This leads to a much lower recovery overhead with the runtime of 52 seconds, compared to the mean 28 seconds of 5 failure-free `parDnC` runtimes.

Chapter 7

Conclusion

7.1 Summary

New approaches to language design and system architecture are needed to address the growing issue of fault tolerance for massively parallel heterogeneous architectures. This thesis investigates the challenges of providing reliable scalable symbolic computing. It has culminated in the design, validation and implementation of a **R**eliable **S**cheduling extension called HdpH-RS.

Chapter 2 presents a critical review of fault tolerance in distributed computing systems, defining dependability terms (Section 2.1) and common existing approaches such as checkpointing, rollback and fault tolerant MPI implementations (Section 2.3). New approaches for scalable fault tolerant language design are needed, and a critique of these existing approaches is given. The SymGridParII middleware and the symbolic computing domain is introduced in Section 2.5. Symbolic computations are challenging to parallelise as they have complex data and control structures, and both dynamic and highly irregular parallelism. The HdpH realisation of the SymGridParII design is described in Section 2.6. The language is a shallowly embedded parallel extension of Haskell that supports high-level implicit and explicit parallelism. To handle the complex nature of symbolic applications, HdpH supports dynamic and irregular parallelism.

The design of a supervised workpool construct [164] (Appendix A.1) is influenced by supervision techniques in Erlang, and task replication in Hadoop (Sections 2.3.6 and 2.3.2). The workpool hides task scheduling, failure detection and task replication from the programmer. For benchmark kernels the supervision overheads are low in the absence of failure, between 2% and 7%, and the increased runtimes are also acceptable in the presence of a single node failure in a ten node architecture, between 8% and 10% (Section A.1.6).

The design of HdpH-RS is an elaboration of the supervised workpools prototype, most notably adding support for fault tolerant work stealing. The concept of pairing one task with one value in the supervised workpool is strengthened with the introduction of the spawn family of primitives (Section 3.3.2). The `spawn` and `spawnAt` primitives are implemented using the existing HdpH primitives `new`, `glob`, `spark`, `pushTo`, and `rput`. These spawn primitives were later added to the HdpH language [113]. The APIs of two new fault tolerant primitives `supervisedSpawn` and `supervisedSpawnAt` in HdpH-RS are identical to the non-fault tolerant versions, providing opt-in fault tolerance to the programmer.

To support these fault tolerance primitives, a reliable scheduler has been designed and verified. The scheduler is designed to handle single, simultaneous and random failures. The scheduling algorithm (Section 3.5.4) is modeled as a Promela abstraction in Section 4.2, and verified with the SPIN model checker. The abstraction includes four nodes. The immortal supervisor node is a node that creates a supervised spark and a supervised future with `supervisedSpawn`. Three other nodes compete for the spark using work stealing and are mortal: they can fail at any time. The supervised future is initially empty. The key property of the model is that in all possible intersections of mortal node failure, the supervised empty future will nevertheless eventually be full. This property is expressed using linear temporal logic formulae. The four nodes are translated in to a finite automaton. The SPIN model checker is used to exhaustively search the intersection of this automaton to validate that the key reliability property holds in all unique model states. This it does having exhaustively searched approximately 8.22 million unique states of the Promela abstraction of the HdpH-RS fishing protocol, at a depth of 124 from the initial state using 85Mb memory for states (Section 4.5).

The verified scheduler design has been implemented in Haskell. A new transport layer for the HdpH-RS scheduler (Section 5.5) propagates TCP errors when connections are lost between nodes. The transport layer was later merged in to the public release 0.0 of HdpH [111]. It informs all nodes of remote node failure, and each node is responsible for ensuring the safety of the futures it supervises. Using the spawn family (Section 5.2), 10 algorithmic skeletons have been developed (Section 6.1.2) to provide high level parallel patterns of computation. Fault tolerant load-balancing and task recovery is masked from the programmer. In extending HdpH, 1 module is added for the fault tolerant strategies, and 14 modules are modified. This amounts to an additional 1271 lines of Haskell code in HdpH-RS, an increase of 52%. The increase is attributed to fault detection, fault recovery and task supervision code.

The small-step operational semantics for HdpH-RS (Section 3.4) extends the HdpH

operational semantics to include the spawn family, and supervised scheduling and task recovery transitions. They provide a concise and unambiguous description of the scheduling transitions in the absence and presence of failure, and the states of supervised sparks and supervised futures. The transition rules are demonstrated with one fault-free execution, and three executions that recover and evaluate tasks in the presence of faults (Section 3.4.4). The execution of the operational semantics in Figure 3.13 demonstrates that scenarios that non-deterministically race pure computations is indistinguishable from fault-free execution, thanks to the idempotent side effect property.

The performance of HdpH-RS in the absence and presence of faults is evaluated on 244 cores of a 32 node COTS architecture i.e. a Beowulf cluster. The scalability of HdpH-RS is measured on 1400 cores of a HPC architecture called HECToR (Chapter 6). Speedup results show that when task sizes are regular, eager scheduling achieves shorter runtimes than lazy on-demand scheduling. A speedup of 757 was achieved using explicit scheduling of Summatory Liouville on HECToR using 1400 cores, and 340 with lazy scheduling. The scalability of hierarchically nested supervision is demonstrated with Mandelbrot implemented with a MapReduce parallel skeleton. Scaling Mandelbrot to 560 cores results in a speedup of 89. The supervision overheads observed when comparing fault tolerant and non-fault tolerant implementations are marginal on the Beowulf cluster and negligible on HECToR at all scales. This demonstrates that HdpH-RS scales to distributed-parallel architectures using both flat and hierarchically nested supervision.

When failure occurrence is frequent, lazy on-demand scheduling is a more appropriate work distribution strategy. Simultaneous failures (Section 6.5.1) and Chaos Monkey failures (Section 6.5.2) are injected to measure recovery costs. Killing 5 nodes in a 20 node COTS architecture at varying stages of a Summatory Liouville execution increases runtime up to 22% when compared to failure free execution. When nodes are killed towards the end of expected computation time, the recovery overheads are negligible with lazy supervised work stealing, as most tasks have by then been evaluated. An instance of injecting failure with Chaos Monkey killed 80% of nodes whilst executing the Queens benchmark also reveal the advantages of lazy on-demand work stealing when failure is the common case and not the exception. The runtime using the two remaining nodes of the initial ten was 52 seconds, compared with the mean runtime of 28 seconds for failure-free runtime with those nodes.

7.2 Limitations

HdpH-RS is limited in the kinds of recoverable computations, and also the built-in assumptions of the communications layer. The recovery of computations is restricted to expressions with idempotent side effects i.e. side effects whose repetition cannot be observed. In the 5 benchmarks used in the evaluation (Chapter 6) all computations are pure, and therefore idempotent. This contrasts with Erlang, which supports the recovery of non-idempotent stateful computation with the task restart parameters of the supervision behaviour API in Erlang OTP.

Unlike the design of a fault tolerant GdH [173], the communications layer in HdpH-RS does not support the addition of nodes during the execution of a single program. Nodes may be lost, and the program will nevertheless be executed provided the root node does not fail. So there may be fewer nodes in the distributed virtual machine at the end of program execution, but not more.

The HdpH-RS communications layer instantiates a fully connected graph of nodes at the start of program execution. Every node is connected via a TCP connection to every other node, a requirement for the fault detection mechanism in HdpH-RS. This topology will be less common in future network infrastructures, where networks will be hierarchically structured or where connections may be managed e.g. set up only on demand.

7.3 Future Work

Fault Tolerant Distributed Data Structures

The focus of this thesis is fault tolerant *big computation*. This is in contrast to fault tolerant *big data* solutions such as MapReduce implementation like Hadoop. The use of distributed data structures is currently out-of-scope for HdpH and HdpH-RS. In order to be regarded a truly distributed programming language, HdpH would need a need to support the persistence of distributed data. Examples are MNesia [120] for Erlang, or HDFS [183] for Hadoop. Resilient distributed data structures is left as future work.

A technique for limiting the cost of failure is memoization. This is especially suited for divide and conquer programming, but is not featured in the divide and conquer skeletons in HdpH-RS. One approach is to use a globalised transposition table to store the values of executed tasks [185]. When tasks are recovered in the presence of failure, this table is first used to check for a result, before rescheduling each task. Supervisors near the top have descendent children spawning potentially many tasks, some of which may have

been executed at the point of failure. The use of transposition tables can avoid the potentially costly re-scheduling of these completed tasks. A distributed data structure is a pre-requisite for a transposition table for the divide and conquer skeletons in HdpH-RS.

Generalised Fault Detecting Transport Layer

The communications layer in HdpH-RS relies on a number of assumptions about the underlying TCP based transport layer. The failure detection exploits the TCP protocol, when transmission attempts to lost endpoints propagates exceptions. In order for nodes to catch these exceptions, a fully connected graph is needed. A generalised communications layer in HdpH-RS could be designed to remove the dependency on a connection-oriented protocol like TCP to support for example, failure detection using passive heartbeats with connectionless protocols like UDP.

Passive Fault Tolerant Fishing Protocol

A less restrictive fault tolerant fishing protocol for HdpH-RS could reduce the number of additional RTS messages needed for supervised work stealing. The fishing protocol in HdpH-RS is the culmination of iterative design guided by the goal of eliminating unlikely, if possible, race conditions identified by the SPIN model checker. The goal for HdpH-RS was not therefore solely to achieve good runtime performance, but to implement a formally verified fishing protocols. Future work could explore an alternative fishing protocol that demotes the supervision intervention to a wholly observational role that can nevertheless be exhaustively verified with SPIN using the key resiliency property defined in this thesis.

Data Structure Performance Tuning

Future versions of HdpH-RS could adopt two recent Haskell technologies. One is a compare-and-swap primitive on top of which lock-free data structures have been developed, including a lock-free work stealing deque. The `monad-par` library will soon adopt (September 2013) a Chase & Lev deque [34] as a lock-free work stealing data structure for threadpools. The author has collaborated with the `atomic-primops` developer whilst exploring its use in HdpH, resulting a GHC bug being uncovered in GHC 7.6 [158]. Adopting the Chase & Lev deque for sparkpools in HdpH is a possibility beyond November 2013, once GHC 7.8 is released. The second is a new multithreaded IO manager for GHC [179], which has been shown to improve multithreaded CloudHaskell performance on multicore hosts. It was motivated by current bottlenecks in network-scale applications. The new IO

manager may lower multithreaded contention between HdpH-RS schedulers and message handlers on future architectures with thousands of cores per node.

Future Architectures

The scalability and recovery performance of HdpH-RS has been measured on a COTS and an HPC architecture with assumptions about failures e.g. that transient failure is nevertheless treated as a permanent loss of service, and of the use cases of these architecture e.g. job managers that deploy jobs on to reserved idle resources.

Resource sharing is increasingly common e.g. virtualised nodes on physical hosts, so node load profiles may fluctuate unpredictably during long-running massively scaled computation. An extension to HdpH-RS could incorporate functionality to forcibly remove otherwise healthy yet overloaded nodes to eliminate unresponsive compute resources. The existing fault tolerance in HdpH-RS would handle such node exits just as if connectivity was lost through permanent failure. Furthermore, the demonstrated safety of racing pure tasks could be used not only for tolerating faults, but also for replicating tasks on unresponsive or overloaded nodes where the effect is indistinguishable from that of no replication, thanks to the idempotence property.

The dynamic scalability of cloud computing infrastructures has not been addressed in this thesis. For example, when a HdpH-RS node fails it can no longer participate in the execution of the job it was detached from. Future HPC use cases may involve the dynamic scale-up and scale-down of compute resources either as budgets allow or as application needs change. Future work would be to adapt HdpH-RS to support the dynamic allocation of nodes to provide an elastic fault tolerant scalable task scheduler for scaling patterns in cloud computing architectures.

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Appendix A

Appendix

A.1 Supervised Workpools

This section presents a software level reliability mechanism, namely supervised fault tolerant workpools implemented in HdpH. The workpool is a feasibility study that influenced the designs of the HdpH-RS scheduler and HdpH-RS fault tolerance primitives. The supervised workpool concept of exposing fault tolerant API primitives later influences the inception of the spawn family of primitives in HdpH-RS (Section 3.3.2). Also, the fault detection and task replication strategies used in the supervised workpool were elaborated upon in HdpH-RS. To the best of the authors knowledge, this was a novel construct at the time time of publication [164] (June, 2012).

The design and implementation of a novel fault-tolerant workpool in Haskell is presented (Sections A.1.1 and A.1.3) hiding task scheduling, failure detection and task replication from the programmer. Moreover, workpools can be nested to form fault-tolerant hierarchies, which is essential for scaling up to massively parallel platforms. Two use cases in the presence of failures are described in Section A.1.2. The implementation of high-level fault tolerant abstractions on top of the workpool are in Section A.1.5: generic fault tolerant skeletons for task parallelism and nested parallelism, respectively. The concept of fault tolerant parallel skeletons is expanded in HdpH-RS, which features 10 fault tolerant skeletons (Section 6.1.2).

The fault tolerant skeletons are evaluated using two benchmarks. These benchmarks demonstrate fault tolerance — computations do complete with a correct result in the presence of node failures. Overheads of the fault tolerant skeletons are measured in Section A.1.6, both in terms of the cost of book keeping, and in terms of the time to recover from failure.

The supervised workpools use a limited scheduling strategy. Tasks are distributed

preemptively, and not on-demand. Once tasks are received, they are converted to threads immediately, sparks are not supported. One elaboration in the HdpH-RS scheduler is a support for supervised sparks, which brings with it a need for a fault tolerant fishing protocol extension from HdpH.

A.1.1 Design of the Workpool

A workpool is an abstract control structure that takes units of work as input, returning values as output. The scheduling of the work units is coordinated by the workpool implementation. Workpools are a very common pattern, and are often used for performance, rather than fault tolerance. For example workpools can be used for limiting concurrent connections to resources, to manage heavy load on compute nodes, and to schedule critical application tasks in favour of non-critical monitoring tasks [175]. The supervised workpool presented in this Section extends the workpool pattern by adding fault tolerance to support reliable execution of HdpH applications. The fault tolerant design is inspired by the supervision behaviour and node monitoring aspects of Erlang (Section 2.3.6), and combines this with Haskell's polymorphic, static typing.

Most workpools schedule work units dynamically, e.g. an idle worker selects a task from the pool and executes it. For simplicity the HdpH workpool uses static scheduling: each worker is given a fixed set of work units (Section A.1.4). The supervised workpool performs well for applications exhibiting regular parallelism, and also for parallel programs with limited irregularity, as shown in Section A.1.6.

Concepts

Before describing the workpool in detail, parts of the HdpH API are re-introduced in Table A.1, with terminology of each primary concept with respect to the workpool. The concepts in HdpH-RS (Section 3.3.1) are a refinement of the supervised workpool terms. First, in HdpH-RS there is less emphasis on GIVar and their respective operations `glob` and `rput`, as these are demoted to internal HdpH-RS scheduling functionality. Secondly, the definition of a *task* in HdpH-RS is refined to be a supervised spark or thread corresponding to a supervised future, or a spark or thread corresponding to a future.

Workpool API

A fundamental principle in the HdpH supervised workpool is that there is a one-to-one correspondence between a *task* and an `IVar` — each task evaluates an expression to return

Table A.1: HdpH and workpool terminology

Concept	Description
IVar	A write-once mutable reference.
GIVar	A global reference to an IVar, which is used to remotely write values to the IVar.
Task	Consists of an *expression* and a *GIVar*. The expression is evaluated, and its value is written to the associated GIVar.
Completed task	When the associated GIVar in a *task* contains the value of the task expression.
Closure	A Serializable expression or value. Tasks and values are serialised as closures, allowing them to be shipped to other nodes.
Supervisor thread	The Haskell thread that has initialised the workpool.
Process	An OS process executing the GHC runtime system.
Supervising process	The *process* hosting the *supervisor thread*.
Supervising node	The node hosting the supervising process.
Worker node	Every node that has been statically assigned a task from a given workpool.

a result which is written to its associated `IVar`. The *tasks* are distributed as closures to *worker nodes*. The *supervisor thread* is responsible for creating and globalising `IVar`s, in addition to creating the associated tasks and distributing them as closures. This one-to-one binding between tasks and `IVar`s by the spawn family of primitives in HdpH-RS (Section 3.3.2). Here are the workpool types and the function for using it:

```
1 type SupervisedTasks a  = [(Closure (IO ()), IVar a)]
2 supervisedWorkpoolEval :: SupervisedTasks a → [NodeId] → IO [a]
```

The `supervisedWorkpoolEval` function takes as input a list of tuples, pairing tasks with their associated `IVar`s, and a list of `NodeId`s. The closured tasks are distributed to worker nodes in a round robin fashion to the specified worker `NodeId`s, and the workpool waits until all tasks are complete i.e. all `IVar`s are full. If a node failure is identified before tasks complete, the unevaluated tasks sent to the failed node are reallocated to the remaining available nodes. Detailed descriptions of the scheduling, node failure detection, and failure recovery is in Section A.1.3.

Workpool Properties and Assumptions

The supervised workpool guarantees that given a list of *tasks*, it will fully evaluate their result provided that:

1. The supervising node is alive throughout the evaluation of all tasks in the workpool.

2. All expressions are computable. For example, evaluating an expression should not throw uncaught exceptions, such as a division by 0; all programming exceptions such as non-exhaustive case statements must be handled within the expression; and so on.

The supervised workpool is non-deterministic, and hence is monadic. This is useful in some cases such as racing the evaluation of the same task on separate nodes. The write operations on `IVar`s are relaxed in HdpH for fault tolerance, allowing two tasks to attempt a write attempt. Either the first to complete evaluation wins, or in the presence of failure the *surviving* task wins. The write semantics of `IVar`s are described in Section A.1.3.

To recover determinism in the supervised workpool, expressions must be *idempotent*. An idempotent expression may be executed more than once which entails the same side effect as executing only once. E.g inserting a given key/value pair to a mutable map - consecutive inserts have no effect. Pure computations, because of their lack of side effects, are of course idempotent.

Workpools are functions and may be freely nested and composed. There is no restriction to the number of workpools hosted on a node, and Section A.1.5 presents a divide-and-conquer abstraction that uses this flexibility.

A.1.2 Use Case Scenarios

Figure A.1 shows a workpool scenario where six closures are created, along with six associated `IVar`s. The closures are allocated to three worker nodes: `Node2, Node3` and `Node4` from the supervising node, `Node1`. Whilst these closures are being evaluated, `Node3` fails, having completed only one of its two tasks. As `IVar i5` had not been filled, closure `c5` is reallocated to `Node4`. No further node failures occur, and once all six `IVar`s are full, the supervised workpool terminates. The mechanisms for detecting node failure, for identifying completed tasks, and the reallocation of closures are described in Section A.1.3.

The use case in Figure A.2 involves the failure the *two* nodes. The scenario is similar to Figure A.1, again involving four nodes, and initial task placement is the same. This time, once `Node2` has evaluated `c1` and `rput` to `i1`, it fails. The task `c4` has not been evaluated, and therefore `IVar i4` is empty. The supervising node `Node1` detects the failure of `Node2` and reallocated `c4` to the only remaining available node, `Node4`. Once all this node has evaluated all allocated tasks (including `c4` from `Node2` and `c5` from `Node3`, all `IVar`s on `Node1` will be full, and STM will unblock, terminating the workpool.

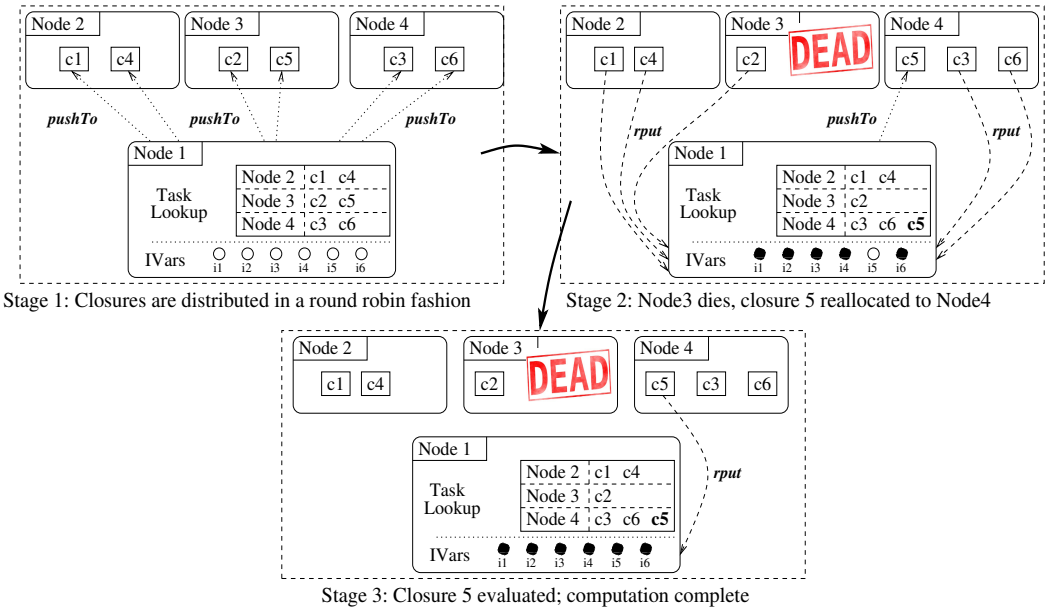

Figure A.1: Reallocating Closures Scenario 1

A.1.3 Workpool Implementation

```
1  -- |HdpH primitives
2  type IVar a = TMVar a                                  -- type synonym for IVar
3  data GIVar a                                           -- global handles to IVars
4  data Closure a                                         -- explicit, serialisable closures
5  pushTo :: Closure (IO ()) → NodeId → IO ()             -- explicit task placement
6  rput   :: GIVar (Closure a) → Closure a → IO ()        -- write a value to a remote IVar
7  get    :: IVar a → IO a                                -- blocking get on an IVar
8  probe  :: IVar a → STM Bool                            -- check if IVar is full or empty
```

Listing A.1: Types Signatures of HdpH Primitives

The types of the relevant HdpH primitives are shown in Listing A.1. These primitives are used as the foundation for the `spawn` family of primitives in HdpH-RS (Chapter 3). The complete fault tolerant workpool implementation is available [161], and the most important functions are shown in Listing A.2. Two independent phases take place in the workpool:

1. Line 5 shows the `supervisedWorkpoolEval` function which creates the workpool, distributes tasks, and then uses Haskell's Software Transactional Memory (STM) library [151] as a termination check described in item 2. The `distributeTasks` function on line 9 uses `pushTo` (from Listing A.1) to ship tasks to the worker nodes and creates `taskLocations`, an instance of `TaskLookup a` (line 3). This is a mutable map from `NodeIds` to `SupervisedTasks a` on line 2, which is used for the book

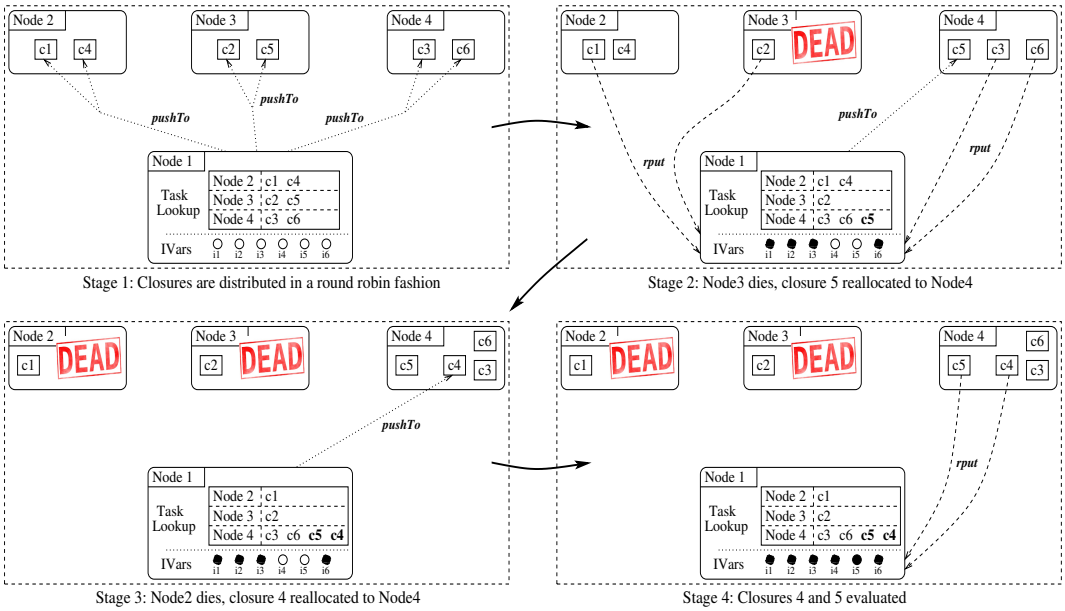

Figure A.2: Reallocating Closures Scenario 2

keeping of task locations. The `monitorNodes` function on lines 23 - 32 then monitors worker node availability. Should a worker node fail, `blockWhileNodeHealthy` (line 30) exits, and `reallocateIncompleteTasks` on line 32 is used to identify incomplete tasks shipped to the failed node, using `probe` (from Listing A.1). These tasks are distributed to the remaining available nodes.

2. STM is used as a termination check. For every task, an `IVar` is created. A `TVar` is created in the workpool to store a list of values returned to these `IVar`s from each task execution. The `getResult` function on line 36 runs a *blocking* `get` on each `IVar`, which then writes this value as an element to the list in the `TVar`. The `waitForResults` function on line 44 is used to keep phase 1 of the supervised workpool active until the length of the list in the `TVar` equals the number of tasks added to the workpool.

The restriction to idempotent tasks in the workpool (Section A.1.1) enables the workpool to freely duplicate and re-distribute tasks. Idempotence is permitted by the write semantics of `IVar`s. The first write to an `IVar` succeeds, and subsequent writes are ignored — successive `rput` attempts to the same `IVar` are non-fatal in HdpH. To support this, the write-once semantics of `IVar`s in the `Par` monad [118] are relaxed slightly in HdpH, to support fault tolerance. This enables identical closures to be raced on separate nodes. Should one of the nodes fail, the other evaluates the closure and `rput`s the value to the associated `IVar`. Should the node failure be intermittent, and a successive `rput` be attempted, it is silently ignored. It also enables replication of closures residing on

```
1  -- |Workpool types
2  type SupervisedTasks a  = [(Closure (IO ()), IVar a)]
3  type TaskLookup a       = MVar (Map NodeId (SupervisedTasks a))
4
5  supervisedWorkpoolEval :: SupervisedTasks a → [NodeId] → IO [a]
6  supervisedWorkpoolEval tasks nodes = do
7          -- PHASE 1
8          -- Ship the work, and create an instance of 'TaskLookup a'.
9     taskLocations ← distributeTasks tasks nodes
10         -- Monitor utilized nodes; reallocate incomplete tasks when worker nodes fail
11    monitorNodes taskLocations
12
13         -- PHASE 2
14         -- Use STM as a termination check. Until all tasks are evaluated,
15         -- phase 1 remains active.
16    fullIvars ← newTVarIO []
17    mapM_ (forkIO ∘ atomically ∘ getResult fullIvars ∘ snd) tasks
18    results ← atomically $ waitForResults fullIvars (length tasks)
19
20         -- Finally, return the results of the tasks
21    return results
22
23 monitorNodes :: TaskLookup a → IO ()
24 monitorNodes taskLookup = do
25    nodes ← fmap Map.keys $ readMVar taskLookup
26    mapM_ (forkIO ∘ monitorNode) nodes
27    where
28     monitorNode :: NodeId → IO ()
29     monitorNode node = do
30       blockWhileNodeHealthy node -- Blocks while node is healthy (Used in Listing A.3)
31       reallocateIncompleteTasks node taskLookup -- reallocate incomplete tasks
32                                                 -- shipped to 'node'
33
34 -- |Takes an IVar, runs a blocking 'get' call, and writes
35 --  the value to the list of values in a TVar
36 getResult :: TVar [a] → IVar a → STM ()
37 getResult values ivar = do
38     v  ← get ivar
39     vs ← readTVar values
40     writeTVar results (vs ++ [v])
41
42 -- |After each write to the TVar in 'evalTask', the length of the list
43 --  is checked. If it matches the number of tasks, STM releases the block.
44 waitForResults :: TVar [a] → Int → STM [a]
45 waitForResults values i = do
46     vs ← readTVar values
47     if length vs == i then return vs else retry
```

Listing A.2: Workpool Implementation and Use of STM as a Termination Check

overloaded nodes to be duplicated on to healthy nodes.

It would be unnecessary and costly to reallocate tasks if they had been fully evaluated prior to the failure of the worker node it was assigned to. For this purpose, the `probe`

primitive is used to identify which IVars are full, indicating the evaluation status of its associated task. As such, all IVars that correspond to tasks allocated to the failed worker node are *probed*. Only tasks associated with empty IVars are reallocated as closures.

Node Failure Detection

A new transport layer for distributed Haskells [43] underlies the fault tolerant workpool. The main advantage of adopting this library is the typed error messages at the Haskell language level. The author contributed to this library as a collaboration with Edsko de Vries and Duncan Coutts on the failure semantics of the transport API [48], and through identifying subtle race conditions in the TCP implementation [47]. The implementation and testing phases coincided with the migration of HdpH over to this TCP based transport API.

```
1    -- connection attempt
2  attempt ← connect myEndPoint remoteEndPointAddress <default args>
3  case attempt of
4    (Left (TransportError ConnectFailed)) → -- react to failure, in Listing A.2 line 30
5    (Right connection) →                    -- otherwise, carry on.
```

Listing A.3: Detecting Node Failure in the `blockWhileNodeHealthy` Function

The `connect` function from the transport layer is shown in Listing A.3. It is used by the workpool to detect node failure in the `blockWhileNodeHealthy` function on line 30 of Listing A.2. Each node creates an endpoint, and endpoints are connected to send and receive messages between the nodes. Node availability is determined by the outcome of connection attempts using `connect` between the node hosting the supervised workpool, and each worker node utilized by that workpool. The transport layer ensures lightweight communications by reusing the underlying TCP connection. One logical connection attempt between the supervising node and worker nodes is made each second. If `Right Connection` is returned, then the worker node is healthy and no action is taken. However, if `Left (TransportError ConnectFailed)` is returned then the worker node is deemed to have failed, and `reallocateIncompleteTasks` (Listing A.2, line 32) redistributes incomplete tasks originally shipped to this node. Concurrency for monitoring node availability is achieved by Haskell IO threads on line 26 in Listing A.2.

An alternative to this design for node failure detection was considered — with periodic heartbeat messages sent from the worker nodes to the process hosting the supervised workpool. However the bottleneck of message delivery would be the same i.e. involving the endpoint of the process hosting the workpool. Moreover, there are dangers with timeout

values for expecting heartbeat messages in asynchronous messaging systems such as the one employed by HdpH. Remote nodes may be wrongly judged to have failed e.g. when the message queue on the workpool process is flooded, and heartbeat messages are not popped from the message queue within the timeout period. Our design avoids this danger by synchronously checking each connection.

Each workpool hosted on a node must monitor the availability of worker nodes. With nested or composed supervised workpools there is a risk that the network will be saturated with `connect` requests to monitor node availability. Our architecture avoids this by creating just one Haskell thread per node that monitors availability of all other nodes, irrespective of the number of workpools hosted on a node. Each supervisor thread communicates with these monitoring threads to identify node failure. See the complete implementation [161] for details.

A.1.4 Workpool Scheduling

One limitation of our supervised workpool is the naive scheduling of tasks between nodes. The strategy is simple — it eagerly distributes the tasks in the workpool between the nodes in a round robin fashion over the ordering of nodes allocated to the workpool. Recall the workpool primitive from Section A.1.1:

```
1 supervisedWorkpoolEval :: SupervisedTasks a → [NodeId] → IO [a]
```

It is up to the programmer to order the `NodeId`s in a sensible sequence. The ordering in the algorithmic skeletons in Section A.1.5 is sensitive to each skeleton. A suitable node order must be selected for each of the skeletons in Section A.1.5. For example, the list of nodes IDs passed to the parallel map are simply sorted in order, and then given to the workpool. In the divide and conquer skeleton, the `NodeId`s are first of all randomised, and are then assigned to the workpool. This avoids overloading nodes near the head of a sorted list of `NodeId`s.

The workpool is eager and preemptive in its scheduling. HdpH-RS has more sophisticated scheduling strategies than the workpool in this chapter, though the recovery and failure detection techniques in HdpH-RS are heavily influenced by the workpool.

A.1.5 Workpool High Level Fault Tolerant Abstractions

It is straight forward to implement algorithmic skeletons in HdpH [114]. This present work extends these by adding resilience to the execution of two generic parallel algorithmic skeletons.

HdpH provides high level coordination abstractions: evaluation strategies and algorithmic skeletons. The advantages of these skeletons are that they provide a higher level of abstraction [172] that capture common parallel patterns, and that the HdpH primitives for work distribution and operations on `IVar`s are hidden away from the programmer.

The following shows how to use fault tolerant workpools to add resilience to algorithmic skeletons. Listing A.4 shows the type signatures of fault tolerant versions of the following two generic algorithmic skeletons.

pushMap A parallel skeleton that provides a parallel map operation, applying a function closure to the input list.

pushDivideAndConquer Another parallel skeleton that allows a problem to be decomposed into sub-problems until they are sufficiently small, and then reassembled with a combining function.

`IVar`s are globalised and closures are created from tasks in the skeleton code, and `supervisedWorkpoolEval` is used at a lower level to distribute closures, and to provide the guarantees described in Section A.1.3. The tasks in the workpool are eagerly scheduled into the threadpool of remote nodes. The two algorithmic skeletons have different scheduling strategies — `pushMap` schedules tasks in a round-robin fashion; `pushDivideAndConquer` schedules tasks randomly (but statically at the beginning, not on-demand).

```
1  pushMap
2     :: [NodeId]          -- available nodes
3     → Closure (a → b) -- function closure
4     → [a]               -- input list
5     → IO [b]            -- output list
6
7  pushDivideAndConquer
8     :: [NodeId]                                          -- available nodes
9     → Closure (Closure a → Bool)                         -- trivial
10    → Closure (Closure a → IO (Closure b))               -- simplySolve
11    → Closure (Closure a → [Closure a])                  -- decompose
12    → Closure (Closure a → [Closure b] → Closure b) -- combine
13    → Closure a                                          -- problem
14    → IO (Closure b)                                     -- output
```

Listing A.4: Fault Tolerant Algorithmic Parallel Skeletons

A.1.6 Supervised Workpool Evaluation

This section present a performance evaluation of the workpools, in both the absence and presence of faults. The fault tolerant parallel skeletons from Section A.1.5 are used to implement a data parallel benchmark and a divide and conquer benchmark.

Data Parallel Benchmark

To demonstrate the `pushMap` data parallel skeleton (Listing A.4), Summatory Liouville [23] has been implemented in HdpH, adapted from existing Haskell code [188]. The Liouville function $\lambda(n)$ is the completely multiplicative function defined by $\lambda(p) = -1$ for each prime p. $L(n)$ denotes the sum of the values of the Liouville function $\lambda(n)$ up to n, where $L(n) := \sum_{k=1}^{n} \lambda(k)$. The *scale-up* runtime results measure Summatory Liouville $L(n)$ for $n = [10^8, 2 \cdot 10^8, 3 \cdot 10^8..10^9]$. Each experiment is run on 20 nodes with closures distributed in a round robin fashion, and the chunk size per closure is 10^6. For example, calculating $L(10^8)$ will generate 100 tasks, allocating 5 to each node. On each node, a partial Summatory Liouville value is further divided and evaluated in parallel, utilising multicore support in the Haskell runtime [116].

Control Parallel Benchmark using Nested Workpools

The `pushDivideAndConquer` skeleton (Listing A.4) is demonstrated with the implementation of Fibonacci. This example illustrates the flexibility of the supervised workpool, which can be nested hierarchically in divide-and-conquer trees. At the point when a closure is deemed too computationally expensive, the problem is decomposed into sub-problems, turned into closures themselves, and pushed to other nodes. In the case of Fibonacci, costly tasks are decomposed into two smaller tasks, though the `pushDivideAndConquer` skeleton permits any number of decomposed tasks to be supervised.

A sequential threshold is used to determine when sequential evaluation should be chosen. For example, if the sequential threshold is 8, and the computation is `fib 10`, then `fib 9` will be further decomposed, whilst `fib 8` will be evaluated sequentially.

The runtime results measure Fibonacci $Fib(n)$ for $n = [45..55]$, and the sequential threshold for each n is 40. Unlike the `pushMap` skeleton, closures are distributed to random nodes from the set of available nodes to achieve fairer load balancing.

Benchmark Platform

The two applications were benchmarked on a Beowulf cluster. Each Beowulf node comprises two Intel quad-core CPUs (Xeon E5504) at 2GHz, sharing 12GB of RAM. Nodes are connected via Gigabit Ethernet and run Linux (CentOS 5.7 64bit). HdpH version 0.3.2 was used and the benchmarks were built with GHC 7.2.1. Benchmarks were run on 20 cluster nodes; to limit variability only 6 cores per node were used. Reported runtime is median wall clock time over 20 executions, and reported error is the range of runtimes.

Supervised Workpool Performance

No Failure The runtimes for Summatory Liouville are shown in Figure A.3. The chunk size is fixed, increasing the number of supervised closures as n is increased in $L(n)$. The overheads of the supervised workpool for Summatory Liouville are shown in Figure A.4. The runtime for Fibonacci are shown in Figure A.5.

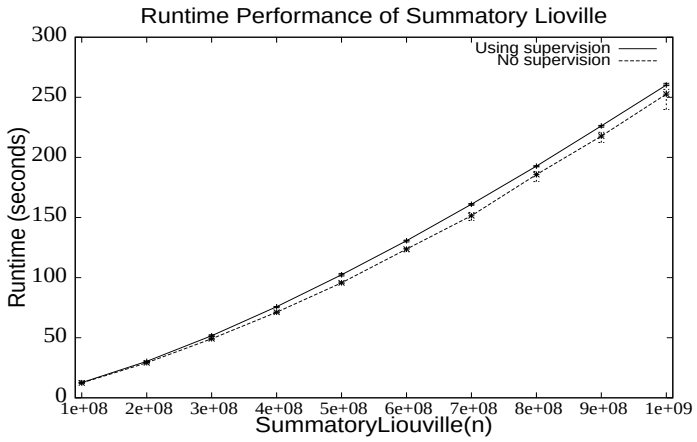

Figure A.3: Runtime with no failures for Summatory Liouville 10^8 to 10^9

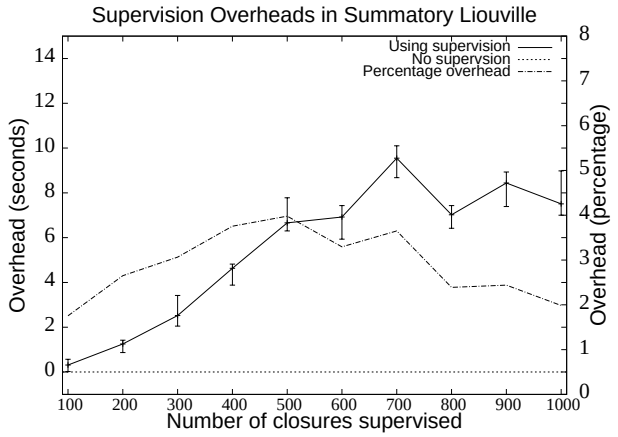

Figure A.4: Supervision overheads with no failures for Summatory Lioville 10^8 to 10^9

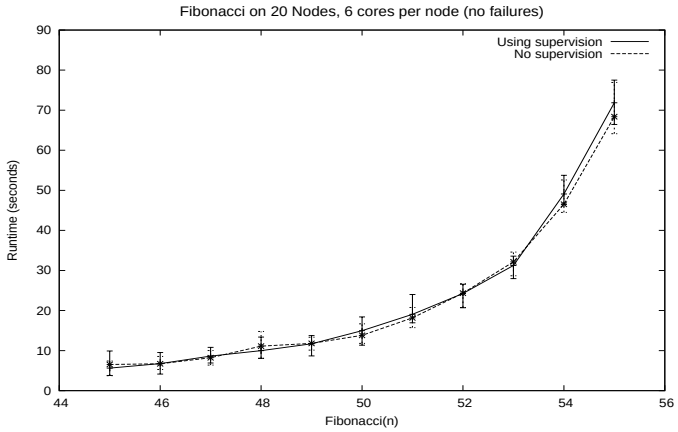

Figure A.5: Runtime with no failure for Fibonacci

The supervision overheads for Summatory Liouville range between 2.5% at $L(10^8)$ and 7% at $L(5 \cdot 10^8)$. As the problem size grows to $L(10^9)$, the number of generated closures increases with the chunk size fixed at 10^6. Despite this increase in supervised closures, near constant overheads of between 6.7 and 8.4 seconds are observed between $L(5 \cdot 10^8)$ and $L(10^9)$.

Overheads are not measurable for Fibonacci, as they are lower than system variability, probably due to random work distribution.

The runtime for calculating $L(5 \cdot 10^8)$ is used to verify the scalability of the HdpH implementation of Summatory Liouville. The median runtime on 20 nodes, each using 6 cores, is 95.69 seconds, and on 1 node using 6 cores is 1711.5 seconds, giving a speed up of 17.9 on 20 nodes.

Recovery From Failure To demonstrate the fault tolerance and to assess the efficacy of the supervised workpool, recovery times have been measured when one node dies during the computation of Summatory Liouville. Nested workpools used by `pushDivideAndConquer` also tolerate faults. Due to the size of the divide-and-conquer graph for large problems, they are harder to analyse in any meaningful way.

To measure the recovery time, a number of parameters are fixed. The computation is $L(3 \cdot 10^8)$ with a chunk size of 10^6, which is initially deployed on 10 nodes, with one hosting the supervising task. The `pushMap` skeleton is used to distribute closures in a round robin fashion, so that 30 closures are sent to each node. An expected runtime utilising 10 nodes is calculated from 5 failure-free executions. From this, approximate timings are calculated for injecting node failure. The Linux `kill` command is used to forcibly terminate one running Haskell process prematurely.

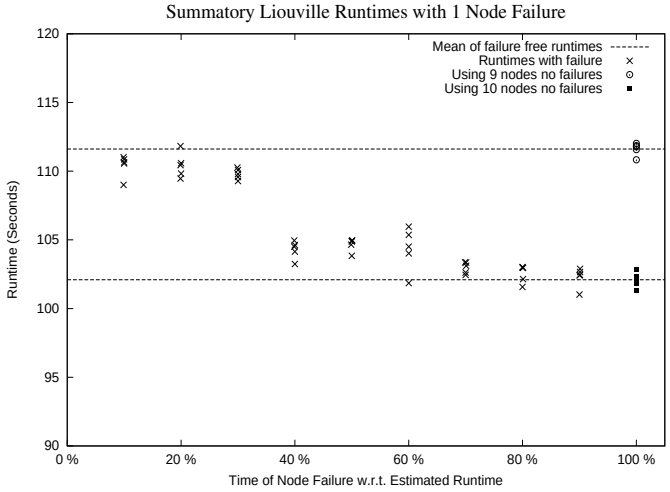

Figure A.6: Recovery time with 1 node failure

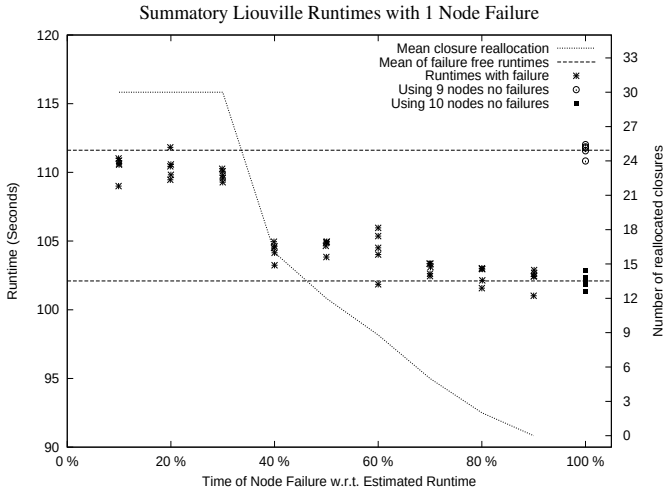

Figure A.7: Recovery time with 1 node failure *with reallocated tasks*

The results in Figure A.6 show the runtime of the Summatory Liouville calculation when node failure occurs at approximately [10%,20%..90%] of expected execution time. Five runtimes are observed at each timing point. Figure A.6 also shows five runtimes using 10 nodes when *no* failures occur, and additionally five runtimes using 9 nodes, again with no failures. Figure A.7 reports an additional dataset — the average number of closures that are reallocated relative to when node failure occurs. As described in Section A.1.3, only non-evaluated closures are redistributed. The expectation is that the longer the injected node failure is delayed, the fewer closures will need reallocating elsewhere.

The data shows that at least for the first 30% of the execution, no tasks are complete on the node, which can be attributed to the time taken to distribute 300 closures. Fully evaluated closure values are seen at 40%, where only 16 (of 30) are reallocated. This continues to fall until the 90% mark, when 0 closures are reallocated, indicating that all closures had already been fully evaluated on the responsible node.

The motivation for observing failure-free runtimes using 9 and also 10 nodes is to evaluate the overheads of recovery time when node failure occurs. Figure A.6 shows that when a node dies early on (in the first 30% of estimated total runtime), the performance of the remaining 9 nodes is comparable with that of a failure-free run on 9 nodes. Moreover, node failure occurring near the end of a run (e.g. at 90% of estimated runtime) does not impact runtime performance, i.e. is similar to that of a 10 node cluster that experiences no failures at all.

A.1.7 Summary

This chapter presents a language based approach to fault tolerant distributed-memory parallel computation in Haskell: a fault tolerant workpool that hides task scheduling, failure detection and task replication from the programmer. Fault tolerant versions of two algorithmic skeletons are developed using the workpool. They provide high level abstractions for fault tolerant parallel computation on distributed-memory architectures. To the best of the authors knowledge the supervised workpool is a novel construct.

The workpool and the skeletons guarantee the completion of tasks even in the presence of multiple node failures, withstanding the failure of all but the supervising node. The supervised workpool has acceptable runtime overheads — between 2.5% and 7% using a data parallel skeleton. Moreover when a node fails, the recovery costs are negligible.

This marks the end of a feasibility study motivated by the claim that HdpH has the potential for fault tolerance [114]. The limitations of the supervised workpools, described in Section A.1.4, are that scheduling is preemptive and eager. There is no load balancing. The ideas of propagated fault detection from the transport layer, and freely replicating idempotent tasks are taken forward into HdpH-RS in Chapter 3.

A.2 Programming with Futures

Programming with futures [95] is a simple programming abstraction for parallel scheduling. A future can be thought of as placeholder for a value that is set to contain a real value once that value becomes known, by evaluating the expression. Futures are created with the HdpH-RS spawn family of primitives (Section 3.3.2). Fault tolerant futures are implemented with HdpH-RS using a modified version of `IVar`s from HdpH, described in Section 5.1.1.

This section compares functional futures in monad-par [118], Erlang RPC [30], and the CloudHaskell Platform (CH-P) [181] with HdpH and HdpH-RS. It shows that HdpH-RS is the only language that provides futures whilst supporting load balancing on distributed-memory architectures (Section A.2.1. It also highlights the inconsistencies between primitive naming conventions for programming with futures (Section A.2.2).

A.2.1 Library Support for Distributed Functional Futures

Table A.2 compares three features of monad-par, CH-P, HdpH and HdpH-RS.

1. Whether the runtime system for these languages balance load between the different processing capabilities dynamically.

API	Load Balancing	Multiple Nodes	Closure transmission	Serialisation
monad-par	✔	✗	-	Not required
Erlang RPC	✗	✔	✔	Built-in language support
CH-P	✗	✔	✔	Template Haskell needed
HdpH	✔	✔	✔	Template Haskell needed
HdpH-RS	✔	✔	✔	Template Haskell needed

Table A.2: Comparison of APIs for Programming with Futures

2. Whether the runtime system can be deployed over multiple nodes.

3. Support for serialising function closures (applies only to multiple-node deployments).

First, monad-par is designed for shared-memory execution with GHC [93] on one node, and load balancing between processor cores. Erlang's RPC library supports multiple node distribution, but does not support work stealing. CH-P is the same as Erlang RPC, but does require additional Template Haskell code for explicit closure creation. Finally, HdpH and HdpH-RS are designed for execution on multiple nodes, and load balancing is between nodes *and* between cores on each node.

A.2.2 Primitive Names for Future Operations

Across these libraries (and many more e.g. [21]), primitives that serve the same purpose unfortunately do not share identical naming conventions. Worse, there are identical primitives names that have different meanings. This section uses the six APIs from Section A.2.1 to compare primitive names, and the presence or absence of key task and future creation primitives in each API.

Table A.3 shows the primitives across the six libraries used for task creation. One common name for task creation is *spawn*. The `spawn` primitive in monad-par and HdpH-RS creates a future and a *future task* primed for lazy work stealing. The same purpose is served by `async` in CH-P. The `spawn/3` and `spawn/4` Erlang primitives are different to both, this time meaning eager task creation and with no enforced relationship to futures. *Arbitrary* tasks are passed to `spawn` in Erlang — there is no obligation to return a value to the parent process.

Table A.4 shows the primitives across the six libraries used for future creation. The Erlang RPC library is for programming with futures, the model of monad-par and HdpH. The function `rpc:async_call/4` eagerly places future tasks, returning a `Key`, synonymous with `IVar`s in monad-par or HdpH-RS. The functions `rpc:yield/1`, `rpc:nb_yield/1` and `rpc:nb_yield/2` are used to read values from keys.

Placement	monad-par	HdpH	HdpH-RS	Erlang	CH	CH-P
Local only	`fork`	`fork`	`fork`	`spawn/3`	`forkProcess`	
Lazy		`spark`				
Eager		`pushTo`		`spawn/4`	`spawn`	
Eager *blocking*				`call/4`	`call`	

Table A.3: Task Creation

Placement	monad-par	HdpH	HdpH-RS	Erlang	CH	CH-P
Local only	`spawn`					`async`
Lazy			`spawn`			
Eager			`spawnAt`	`async_call/4`		`asyncSTM`

Table A.4: Future Creation

The Fibonacci micro-benchmark is used to compare the use of the Erlang, HdpH-RS and CH-P libraries for *future task* creation for distributed-memory scheduling. The decomposition of Fibonacci is the same in all three cases. The scheduling in Erlang and CH-P is explicit, whilst in HdpH-RS it is lazy.

Listing A.5 shows an Erlang Fibonacci that uses `rpc:async_call` on line 8. Listing A.6 shows a HdpH-RS Fibonacci that uses a `spawn` call on line 6. Listing A.7 shows a CH-P Fibonacci that uses an `asyncSTM` on line 11.

```
1  -module(fib_rpc).
2  -export([fib/1,random_node/0]).
3
4  %% Compute Fibonacci with futures
5  fib(0) -> 0;
6  fib(1) -> 1;
7  fib(X) ->
8    Key = rpc:async_call(random_node(),fib_rpc,fib,[X-1]),
9    Y = fib(X-2),
10   Z = rpc:yield(Key),
11   Y + Z.
12
13 %% Select random node (maybe our own)
14 random_node() ->
15   I = random:uniform(length(nodes()) + 1),
16   Nodes = nodes() ++ [node()],
17   lists:nth(I,Nodes).
```

Listing A.5: Fibonacci with Asynchronous Remote Function Calls in Erlang with RPC

The `mkClosure` Template Haskell in HdpH-RS is required to allow the `fib` function to

```
1  fib :: Int → Par Integer
2  fib x
3      | x == 0 = return 0
4      | x == 1 = return 1
5      | otherwise = do
6          v ← spawn $(mkClosure [| hdphFibRemote (x) |])
7          y ← fib (x - 2)
8          clo_x ← get v
9          force $ unClosure clo_x + y
10
11 hdphFibRemote :: Int → Par (Closure Integer)
12 hdphFibRemote n =
13   fib (n-1) >>= force ∘ toClosure
```

Listing A.6: Fibonacci with HdpH-RS

```
1  randomElement :: [a] → IO a
2  randomElement xs = randomIO >>= λix → return (xs !! (ix `mod` length xs))
3
4  remotableDecl [
5    [d| fib :: ([NodeId],Int) → Process Integer ;
6        fib (_,0) = return 0
7        fib (_,1) = return 1
8        fib (nids,n) = do
9          node ← liftIO $ randomElement nids
10         let tsk = remoteTask ($(functionTDict 'fib)) node ($(mkClosure 'fib) (nids,n-2))
11         future ← asyncSTM tsk
12         y ← fib (nids,n-1)
13         (AsyncDone z) ← wait future
14         return $ y + z
15     |]
16   ]
```

Listing A.7: Fibonacci with Async CloudHaskell-Platform API

be transmitted over the network. The CH-P code uncovered a race condition when setting up monitors for evaluating `AsyncTask`s, which was added as a test case upstream by the author [159]. The difference between HdpH-RS and CH-P is that in CH-P a `NodeId` must be given to `asyncSTM` in CH-P, to eagerly schedule a `fib (n-2)` task, selected with `randomElement` on line 2. There are more intrusive Template Haskell requirements in CloudHaskell, as it does not share a common closure representation with HdpH. In CloudHaskell, the `remotableDecl` boilerplate code is needed when a programmer wants to refer to `$(mkClosure 'f)` within the definition of `f` itself.

The CH-P API implementation uses Haskell's STM to monitor the evaluation status of `Async`'s on line 11 in Listing A.7. The same technique is used for blocking on `IVar`s in the supervised workpools implementation for HdpH in Chapter A.1.

	monad-par	HdpH	HdpH-RS	Erlang	CH	CH-P
Blocking read	`get`	`get`	`get`	`yield/1`		`wait`
Non-blocking read		`tryGet`	`tryGet`	`nb_yield/1`		`poll`
Timeout read				`nb_yield/2`		`waitTimeout`
Check fullness		`probe`	`probe`			`check`

Table A.5: Operations on Futures

It is a similar story for operations on futures. In HdpH and HdpH-RS, a blocking wait on a future is `get`, which is also true for monad-par. In Erlang RPC it is `rpc:yield/4`, and in CH-P it is `wait`. The non-blocking version in HdpH and HdpH-RS is `tryGet`, in Erlang RPC it is `rpc:nb_yield/4` and in CH-P it is `waitTimeout`. The operations on futures are shown in Table A.5.

This section has expanded on the introduction of the spawn family in Section 3.3.2. It shows that HdpH balances load between processing elements. In contrast to the monad-par library which defines single-node multicores as a processing element, HdpH uses distributed-memory multicore as processing elements. Moreover, HdpH-RS shares the futures programming model with the Erlang RPC library and the CloudHaskell Platform on distributed-memory. Only the HdpH-RS runtime supports load-balancing for evaluating futures.

The second distinction in this section is the naming conventions for creating futures. The *spawn* convention in HdpH-RS was influenced by the monad-par API. It also uses `IVar`s as futures. As HdpH was designed as a distributed-memory extension of this library, the spawn name is shared. In contrast, the CloudHaskell Platform primitive for eager task placement is `asyncSTM`. The Erlang primitive for eager task placement is `async_call/4`. The `spawn` and `supervisedSpawn` HdpH-RS primitives are unique in their function, in this comparison of three functional libraries. They are used to create supervised sparks that are lazily scheduled with load balancing on distributed-memory.

A.3 Promela Model Implementation

The Promela model used in Chapter 4 is in Listing A.8.

```
1  mtype = {FISH,DEADNODE,SCHEDULE,REQ,AUTH,DENIED,ACK,NOWORK,OBSOLETE,RESULT};
2  mtype = {ONNODE,INTRANSITION};
3
4  typedef Location
5  {
6    int from;
7    int to;
8    int at=3;
9  }
```

```
10
11 typedef Sparkpool {
12   int spark_count=0;
13   int spark=0; /* sequence number */
14 }
15
16 typedef Spark {
17   int highestReplica=0;
18   Location location;
19   mtype context=ONNODE;
20   int age=0;
21 }
22
23 typedef WorkerNode {
24   Sparkpool sparkpool;
25   int waitingFishReplyFrom;
26   bool waitingSchedAuth=false;
27   bool resultSent=false;
28   bool dead=false;
29   int lastTried;
30 };
31
32 typedef SupervisorNode {
33   Sparkpool sparkpool;
34   bool waitingSchedAuth=false;
35   bool resultSent=false;
36   bit ivar=0;
37 };
38
39 #define null -1
40 #define maxLife 100
41
42 WorkerNode worker[3];
43 SupervisorNode supervisor;
44 Spark spark;
45 chan chans[4] = [10] of {mtype, int , int , int } ;
46
47 inline report_death(me){
48   chans[0] ! DEADNODE(me, null, null) ;
49   chans[1] ! DEADNODE(me, null, null) ;
50   chans[2] ! DEADNODE(me, null, null) ;
51   chans[3] ! DEADNODE(me, null, null) ; /* supervisor */
52 }
53
54 active proctype Supervisor() {
55   int thiefID, victimID, deadNodeID, seq, authorizedSeq, deniedSeq;
56
57   supervisor.sparkpool.spark_count = 1;
58   run Worker(0); run Worker(1); run Worker(2);
59
60 SUPERVISOR_RECEIVE:
61
62   if  :: (supervisor.sparkpool.spark_count > 0 && spark.age > maxLife) →
63          atomic {
64            supervisor.resultSent = 1;
65            supervisor.ivar = 1;  /* write to IVar locally */
66            goto EVALUATION_COMPLETE;
67          }
68       :: else →
69          if
70            :: (supervisor.sparkpool.spark_count > 0) →
71               atomic {
72                 supervisor.resultSent = 1;
73                 supervisor.ivar = 1;  /* write to IVar locally */
74                 goto EVALUATION_COMPLETE;
75               }
76            :: chans[3] ? DENIED(thiefID, deniedSeq,null) →
77               supervisor.waitingSchedAuth = false;
78               chans[thiefID] ! NOWORK(3, null, null) ;
79            :: chans[3] ? FISH(thiefID, null,null) → /* React to FISH request */
80               if    /* We have the spark */
81                 :: (supervisor.sparkpool.spark_count > 0 && !supervisor.waitingSchedAuth) →
```

```
82                    supervisor.waitingSchedAuth = true;
83                    chans[3] ! REQ(3, thiefID, supervisor.sparkpool.spark);
84                 ::  else → chans[thiefID] ! NOWORK(3, null,null) ; /*We don't have the spark */
85              fi;
86           :: chans[3] ? AUTH(thiefID, authorizedSeq, null) → /* React to FISH request */
87              d_step {
88                supervisor.waitingSchedAuth = false;
89                supervisor.sparkpool.spark_count--;
90              }
91              chans[thiefID] ! SCHEDULE(3, supervisor.sparkpool.spark ,null);
92           :: chans[3] ? REQ(victimID, thiefID, seq) →
93              if
94                :: seq == spark.highestReplica →
95                   if
96                     :: spark.context == ONNODE && ! worker[thiefID].dead→
97                        d_step {
98                          spark.context  = INTRANSITION;
99                          spark.location.from = victimID ;
100                         spark.location.to = thiefID ;
101                       }
102                       chans[victimID] ! AUTH(thiefID, seq, null);
103                    :: else →
104                       chans[victimID] ! DENIED(thiefID, seq, null);
105                  fi
106               :: else →
107                  chans[victimID] ! OBSOLETE(thiefID, null, null); /* obsolete sequence number */
108             fi
109          :: chans[3] ? ACK(thiefID, seq, null) →
110             if
111               :: seq == spark.highestReplica →
112                  d_step {
113                    spark.context = ONNODE;
114                    spark.location.at = thiefID ;
115                  }
116               :: else → skip ;
117             fi
118          :: atomic {chans[3] ? RESULT(null, null, null); supervisor.ivar = 1; goto EVALUATION_COMPLETE;}
119          :: chans[3] ? DEADNODE(deadNodeID, null, null) →
120             bool should_replicate;
121             d_step {
122               should_replicate = false;
123               if
124                 :: spark.context == ONNODE \
125                    && spark.location.at == deadNodeID → should_replicate = true;
126                 :: spark.context  == INTRANSITION \
127                    && (spark.location.from == deadNodeID \
128                        || spark.location.to == deadNodeID) → should_replicate = true;
129                 :: else → skip;
130               fi;
131
132               if
133                 :: should_replicate →
134                    spark.age++;
135                    supervisor.sparkpool.spark_count++;
136                    spark.highestReplica++;
137                    supervisor.sparkpool.spark = spark.highestReplica ;
138                    spark.context = ONNODE;
139                    spark.location.at = 3 ;
140                 :: else → skip;
141               fi;
142             }
143       fi;
144  fi;
145
146  if
147    :: (supervisor.ivar == 0) → goto SUPERVISOR_RECEIVE;
148    :: else → skip;
149  fi;
150
151 EVALUATION_COMPLETE:
152
153 }  /* END OF SUPERVISOR */
```

```
154
155 proctype Worker(int me) {
156   int thiefID, victimID, deadNodeID, seq, authorisedSeq, deniedSeq;
157
158 WORKER_RECEIVE:
159
160   if
161     :: (worker[me].sparkpool.spark_count > 0 && spark.age > maxLife) →
162        atomic {
163          worker[me].resultSent = true;
164          chans[3]  ! RESULT(null,null,null);
165          goto END;
166        }
167
168     :: else →
169        if
170          ::  skip →  /* die */
171             worker[me].dead = true;
172             report_death(me);
173             goto END;
174
175          :: (worker[me].sparkpool.spark_count > 0) →
176               chans[3] ! RESULT(null,null,null);
177
178          :: (worker[me].sparkpool.spark_count == 0 && (worker[me].waitingFishReplyFrom == -1) \
179              && spark.age < (maxLife+1)) →
180             /* Lets go fishing */
181             int chosenVictimID;
182             d_step {
183               if
184                 :: (0 != me) && !worker[0].dead  && (worker[me].lastTried -  0) → chosenVictimID = 0;
185                 :: (1 != me) && !worker[1].dead  && (worker[me].lastTried -  1) → chosenVictimID = 1;
186                 :: (2 != me) && !worker[2].dead  && (worker[me].lastTried -  2) → chosenVictimID = 2;
187                 :: skip → chosenVictimID = 3; /* supervisor */
188               fi;
189               worker[me].lastTried=chosenVictimID;
190               worker[me].waitingFishReplyFrom = chosenVictimID;
191             };
192             chans[chosenVictimID] ! FISH(me, null, null) ;
193
194          :: chans[me] ? NOWORK(victimID, null, null) →
195               worker[me].waitingFishReplyFrom = -1;  /* can fish again */
196
197          :: chans[me] ? FISH(thiefID, null, null) → /* React to FISH request */
198             if   /* We have the spark */
199               :: (worker[me].sparkpool.spark_count > 0 && ! worker[me].waitingSchedAuth) →
200                  worker[me].waitingSchedAuth = true;
201                  chans[3] ! REQ(me, thiefID, worker[me].sparkpool.spark);
202               ::  else → chans[thiefID] ! NOWORK(me, null, null) ; /*We don't have the spark */
203             fi
204
205          :: chans[me] ? AUTH(thiefID, authorisedSeq, null) →  /* React to schedule authorisation */
206             d_step {
207               worker[me].waitingSchedAuth = false;
208               worker[me].sparkpool.spark_count--;
209               worker[me].waitingFishReplyFrom = -1;
210             }
211             chans[thiefID] ! SCHEDULE(me, worker[me].sparkpool.spark, null);
212
213          :: chans[me] ? DENIED(thiefID, deniedSeq, null) →
214             worker[me].waitingSchedAuth = false;
215             chans[thiefID] ! NOWORK(me, null, null) ;
216
217          :: chans[me] ? OBSOLETE(thiefID, null, null) →
218             d_step {
219               worker[me].waitingSchedAuth = false;
220               worker[me].sparkpool.spark_count--;
221               worker[me].waitingFishReplyFrom = -1;
222             }
223             chans[thiefID] ! NOWORK(me, null, null) ;
224
225          :: chans[me] ? SCHEDULE(victimID, seq, null) → /* We're being sent the spark */
```

```
226             d_step {
227               worker[me].sparkpool.spark_count++;
228               worker[me].sparkpool.spark = seq ;
229               spark.age++;
230             }
231             chans[3] ! ACK(me, seq, null) ; /* Send ACK To supervisor */
232
233          :: chans[me] ? DEADNODE(deadNodeID, null, null) →
234             d_step {
235               if
236                 :: worker[me].waitingFishReplyFrom > deadNodeID →
237                    worker[me].waitingFishReplyFrom = -1 ;
238                 :: else → skip ;
239               fi ;
240             };
241        fi ;
242   fi;
243
244   if
245     :: (supervisor.ivar == 1) → goto END;
246     :: else → goto WORKER_RECEIVE;
247   fi;
248
249 END:
250
251 } /* END OF WORKER */
252
253 /* propositional symbols for LTL formulae */
254
255 #define ivar_full ( supervisor.ivar == 1 )
256 #define ivar_empty ( supervisor.ivar == 0 )
257 #define all_workers_alive ( !worker[0].dead && !worker[1].dead && !worker[2].dead )
258 #define all_workers_dead ( worker[0].dead && worker[1].dead && worker[2].dead )
259 #define any_result_sent ( supervisor.resultSent \
260                           || worker[0].resultSent
261                           || worker[1].resultSent \
262                           || worker[2].resultSent )
263
264 /* SPIN generated never claims corresponding to LTL formulae */
265
266 never  {    /* ! [] all_workers_alive */
267 T0_init:
268   do
269     :: d_step { (! ((all_workers_alive))) → assert(!(! ((all_workers_alive)))) }
270     :: (1) → goto T0_init
271   od;
272 accept_all:
273   skip
274 }
275
276 never  {    /* ! [] (ivar_empty U any_result_sent) */
277   skip;
278 T0_init:
279   do
280     :: (! ((any_result_sent))) → goto accept_S4
281     :: d_step { (! ((any_result_sent)) && ! ((ivar_empty))) →
282                 assert(!(! ((any_result_sent)) && ! ((ivar_empty)))) }
283     :: (1) → goto T0_init
284   od;
285 accept_S4:
286   do
287     :: (! ((any_result_sent))) → goto accept_S4
288     :: d_step { (! ((any_result_sent)) && ! ((ivar_empty))) →
289                 assert(!(! ((any_result_sent)) && ! ((ivar_empty)))) }
290   od;
291 accept_all:
292   skip
293 }
294
295 never  {    /* ! <> [] ivar_full */
296 T0_init:
297   do
```

```
298     :: (! ((ivar_full))) → goto accept_S9
299     :: (1) → goto T0_init
300   od;
301 accept_S9:
302   do
303     :: (1) → goto T0_init
304   od;
305 }
```

Listing A.8: Promela Model of HdpH-RS Scheduler

A.4 Feeding Promela Bug Fix to Implementation

This section shows the Promela fix (Section A.4.1) and Haskell fix (Section A.4.2) to the scheduling bug described in Section 4.6.

A.4.1 Bug Fix in Promela Model

```
commit 7f23a46035cbb9a12aeadb84ab8dbcb0c28e7a48
Author: Rob Stewart <robstewart57@gmail.com>
Date:   Thu Jun 27 23:21:20 2013 +0100

    Additional condition when supervisor receives REQ.

    Now the supervisor checks that the thief in a REQ message is still
    alive before it authorises with the scheduling with AUTH. This has
    been fed back in to the HdpH-RS implementation git commit
    d2c5c7e58257ae11443c00203a9cc984b13601ad

diff --git a/spin_models/hdph_scheduler.pml b/spin_models/hdph_scheduler.pml
index 3bb033f..e94ce63 100644
--- a/spin_models/hdph_scheduler.pml
+++ b/spin_models/hdph_scheduler.pml
  :: chans[3] ? REQ(sendingNode, fishingNodeID, seq) ->
     if
       :: seq == spark.highestReplica ->
          if
-          :: spark.context == ONNODE ->
+          :: spark.context == ONNODE && ! worker[fishingNodeID].dead->
              atomic {
                spark.context  = INTRANSITION;
                spark.location.from = sendingNode ;
                spark.location.to = worker[fishingNodeID].inChan;
              }
              sendingNode ! AUTH(worker[fishingNodeID].inChan, seq);
           :: else ->
              sendingNode ! DENIED(worker[fishingNodeID].inChan, seq);
```

A.4.2 Bug Fix in Haskell

```
commit d2c5c7e58257ae11443c00203a9cc984b13601ad
Author: Rob Stewart <robstewart57@gmail.com>
```

```
Date: Thu Jun 27 23:05:45 2013 +0100

    Added guard in handleREQ.

    Improvements (a simplification) to Promela model has enabled me to
    attempt to verify more properties. Attempting to verify a new
    property has uncovered a subtle deadlock in the fault tolerant
    fishing. A thief chooses a random victim and the victim requests a
    SCHEDULE to the supervisor of the spark. The supervisor may
    receive a DEADNODE message about the thief before the REQ. When
    the REQ is received by the supervisor, the existence of the thief
    in the VM is not checked, so the supervisor may nevertheless
    return AUTH to the victim. The victim will blindly send the
    message to the dead node, and the spark may be lost. The
    supervisor will have no future DEADNODE message about the thief to
    react to i.e. the spark will not get recreated.

    Now, the spark supervisor checks that the thief is in the VM
    before sending an AUTH to the victim. The spark location record
    now is InTransition. If the supervisor /now/ receives a DEADNODE
    message, it *will* re-create the spark, with an incremented
    replica number.

diff --git a/hdph/src/Control/Parallel/HdpH/Internal/Sparkpool.hs
           b/hdph/src/Control/Parallel/HdpH/Internal/Sparkpool.hs
index 480e938..205151d 100644
--- a/hdph/src/Control/Parallel/HdpH/Internal/Sparkpool.hs
+++ b/hdph/src/Control/Parallel/HdpH/Internal/Sparkpool.hs
@@ -608,25 +608,35 @@ handleREQ (REQ taskRef seqN from to) = do
             show obsoleteMsg ++ " ->> " ++ show from
           void $ liftCommM $ Comm.send from $ encodeLazy obsoleteMsg
         else do
-         loc <- liftIO $ fromJust <$> locationOfTask taskRef
-         case loc of

+         nodes <- liftCommM Comm.allNodes
+         -- check fisher hasn't died in the meantime (from verified model)
+         if (elem to nodes)
+          then do
+           loc <- liftIO $ fromJust <$> locationOfTask taskRef
+           case loc of

+          else do
+           let deniedMsg = DENIED to
+           debug dbgMsgSend $
+              show deniedMsg ++ " ->> " ++ show from
+           void $ liftCommM $ Comm.send from $ encodeLazy deniedMsg
```

A.5 Network Transport Event Error Codes

All typed error events that can be received from the network-transport [44] layer is in Listing A.9. The API for error event codes was conceived by the WellTyped company [182] as part of the CloudHaskell 2.0 development [43]. The `ErrorConnectionLost` error

is used in HdpH-RS to propagate `DEADNODE` messages to the scheduler.

```
1  -- | Error codes used when reporting errors to endpoints (through receive)
2  data EventErrorCode =
3      -- | Failure of the entire endpoint
4      EventEndPointFailed
5      -- | Transport-wide fatal error
6    | EventTransportFailed
7      -- | We lost connection to another endpoint
8      --
9      -- Although "Network.Transport" provides multiple independent lightweight
10     -- connections between endpoints, those connections cannot fail
11     -- independently: once one connection has failed, all connections, in
12     -- both directions, must now be considered to have failed; they fail as a
13     -- "bundle" of connections, with only a single "bundle" of connections per
14     -- endpoint at any point in time.
15     --
16     -- That is, suppose there are multiple connections in either direction
17     -- between endpoints A and B, and A receives a notification that it has
18     -- lost contact with B. Then A must not be able to send any further
19     -- messages to B on existing connections.
20     --
21     -- Although B may not realise immediately that its connection to A has
22     -- been broken, messages sent by B on existing connections should not be
23     -- delivered, and B must eventually get an EventConnectionLost message,
24     -- too.
25     --
26     -- Moreover, this event must be posted before A has successfully
27     -- reconnected (in other words, if B notices a reconnection attempt from A,
28     -- it must post the EventConnectionLost before acknowledging the connection
29     -- from A) so that B will not receive events about new connections or
30     -- incoming messages from A without realising that it got disconnected.
31     --
32     -- If B attempts to establish another connection to A before it realised
33     -- that it got disconnected from A then it's okay for this connection
34     -- attempt to fail, and the EventConnectionLost to be posted at that point,
35     -- or for the EventConnectionLost to be posted and for the new connection
36     -- to be considered the first connection of the "new bundle".
37   | EventConnectionLost EndPointAddress
```

Listing A.9: Error Events in Transport Layer

A.6 Handling Dead Node Notifications

The handling of `DEADNODE` messages in the HdpH-RS scheduler is in Listing A.10. The implementations of `replicateSpark` and `replicateThread` (lines 22 and 23) is in Appendix A.7.

```
1  handleDEADNODE :: Msg RTS → RTS ()
2  handleDEADNODE (DEADNODE deadNode) = do
3      -- remove node from virtual machine
4      liftCommM $ Comm.rmNode deadNode
```

```
5
6       -- 1) if waiting for FISH response from dead node, reset
7       maybe_fishingReplyNode ← liftSparkM waitingFishingReplyFrom
8       when (isJust maybe_fishingReplyNode) $ do
9         let fishingReplyNode = fromJust maybe_fishingReplyNode
10        when (fishingReplyNode == deadNode) $ do
11          liftSparkM clearFishingFlag
12
13      -- 2) If spark in guard post was destined for
14      --    the failed node, put spark back in sparkpool
15      liftSparkM $ popGuardPostToSparkpool deadNode
16
17      -- 3a) identify all empty vulnerable futures
18      emptyIVars ← liftIO $ vulnerableEmptyFutures deadNode :: RTS [(Int,IVar m a)]
19      (emptyIVarsSparked,emptyIVarsPushed) ← partitionM wasSparked emptyIVars
20
21      -- 3b) create replicas
22      replicatedSparks  ← mapM (liftIO ∘ replicateSpark) emptyIVarsSparked
23      replicatedThreads ← mapM (liftIO ∘ replicateThread) emptyIVarsPushed
24
25      -- 3c) schedule replicas
26      mapM_ (liftSparkM ∘ putSpark ∘ Left ∘ toClosure ∘ fromJust) replicatedSparks
27      mapM_ (execThread ∘ mkThread ∘ unClosure ∘ fromJust) replicatedThreads
28
29      -- for RTS stats
30      replicateM_ (length emptyIVarsSparked) $ liftSparkM $ getSparkRecCtr  >>= incCtr
31      replicateM_ (length emptyIVarsPushed)  $ liftSparkM $ getThreadRecCtr >>= incCtr
32
33    where
34      wasSparked (_,v) = do
35        e ← liftIO $ readIORef v
36        let (Empty _ maybe_st) = e
37            st = fromJust maybe_st
38        return $ scheduling st == Sparked
```

Listing A.10: Handler for `DEADNODE` Messages

A.7 Replicating Sparks and Threads

Listing A.11 shows the implementation of `replicateSpark` and `replicateThread`. These are used by `handleDEADNODE` in Listing A.10 of Appendix A.6 to recover at-risk tasks when node failure is detected.

```
1  replicateSpark :: (Int,IVar m a) → IO (Maybe (SupervisedSpark m))
2  replicateSpark (indexRef,v) = do
3    me ← myNode
4    atomicModifyIORef v $ λe →
5      case e of
6        Full _ → (e,Nothing) -- cannot duplicate task, IVar full, task garbage collected
7        Empty b maybe_st →
8          let ivarSt = fromMaybe
9                (error "cannot␣duplicate␣non-supervised␣task")
10               maybe_st
```

```
11              newTaskLocation =  OnNode me
12              newReplica = (newestReplica ivarSt) + 1
13              supervisedTask = SupervisedSpark
14                { clo = task ivarSt
15                , thisReplica = newReplica
16                , remoteRef = TaskRef indexRef me
17                }
18              newIVarSt = ivarSt { newestReplica = newReplica , location = newTaskLocation}
19          in (Empty b (Just newIVarSt),Just supervisedTask)
20
21  replicateThread :: (Int,IVar m a) → IO (Maybe (Closure (ParM m ())))
22  replicateThread (indexRef,v) = do
23    me ← myNode
24    atomicModifyIORef v $ λe →
25      case e of
26        Full _ → (e,Nothing) -- cannot duplicate task, IVar full, task garbage collected
27        Empty b maybe_st →
28          let ivarSt = fromMaybe
29               (error "cannot␣duplicate␣non-supervised␣task")
30               maybe_st
31              newTaskLocation =  OnNode me
32              newReplica = (newestReplica ivarSt) + 1
33              threadCopy = task ivarSt
34              newIVarSt = ivarSt { newestReplica = newReplica , location = newTaskLocation}
35          in (Empty b (Just newIVarSt),Just threadCopy)
```

Listing A.11: Replicating Sparks & Threads in Presence of Failure

A.8 Propagating Failures from Transport Layer

The implementation of the `receive` function in the `Comm` module of HdpH-RS is in Listing A.12.

```
1  receive :: IO Msg
2  receive = do
3       ep ← myEndPoint
4       event ← NT.receive ep
5       case event of
6          -- HdpH-RS payload message
7          NT.Received _ msg →  return ((force ∘ decodeLazy ∘ Lazy.fromChunks) msg)
8
9          -- special event from the transport layer
10         NT.ErrorEvent (NT.TransportError e _) →
11          case e of
12           (NT.EventConnectionLost ep) → do
13                mainEP ← mainEndpointAddr
14                if mainEP == ep then do
15                  -- check if the root node has died. If it has, give up.
16                  uncleanShutdown
17                  return Shutdown
18
19                 else do
20                  -- propagate DEADNODE to the scheduler
```

```
21                  remoteConnections ← connectionLookup
22                  let x = Map.filterWithKey (λnode _ → ep == node) remoteConnections
23                      deadNode = head $ Map.keys x
24                      msg = Payload $ encodeLazy (Payload.DEADNODE deadNode)
25                  return msg
26
27            _ → receive -- loop
28          -- unused events: [ConnectionClosed,ConnectionOpened,
29          --                 ReceivedMulticast,EndPointClosed]
30          _ → receive
```

Listing A.12: Propagating Failure Events

A.9 HdpH-RS Skeleton API

The HdpH-RS algorithmic skeletons API is in Listing A.13. They are evaluated in Chapter 6. They are adaptions of HdpH skeletons, which are available online [110]. The use of `spawn` and `spawnAt` in the HdpH skeletons is replaced with `supervisedSpawn` and `supervisedSpawnAt` respectively in the HdpH-RS versions.

```
1  ------------------------
2  -- parallel-map family
3
4  parMap
5    :: (ToClosure a, ForceCC b)
6    ⇒ Closure (a → b) -- function to apply
7    → [a]             -- list of inputs
8    → Par [b]         -- list of outputs
9
10 pushMap
11   :: (ToClosure a, ForceCC b)
12   ⇒ Closure (a → b)  -- function to apply
13   → [a]               -- list of inputs
14   → Par [b]           -- list of outputs
15
16 parMapForkM
17   :: (NFData b
18   ⇒ (a → Par b)  -- function to apply
19   → [a]          -- list of inputs
20   → Par [b]      -- list of outputs
21
22 parMapChunked
23   :: (ToClosure a, ForceCC b)
24   ⇒ Int              -- how many chunks
25   → Closure (a → b) -- function to apply
26   → [a]             -- list of inputs
27   → Par [b]         -- list of outputs
28
29 pushMapChunked
30   :: (ToClosure a, ForceCC b)
31   ⇒ Int              -- how many chunks
32   → Closure (a → b) -- function to apply
```

```
33    → [a]              -- list of inputs
34    → Par [b]          -- list of outputs
35
36  parMapSliced
37    :: (ToClosure a, ForceCC b)
38    ⇒ Int               -- how many slices
39    → Closure (a → b)  -- function to apply
40    → [a]               -- list of inputs
41    → Par [b]           -- list of outputs
42
43  pushMapSliced
44    :: (ToClosure a, ForceCC b)
45    ⇒ Int               -- how many slices
46    → Closure (a → b)  -- function to apply
47    → [a]               -- list of inputs
48    → Par [b]           -- list of outputs
49
50  ------------------------
51  -- divide-and-conquer family
52
53  forkDivideAndConquer
54    :: (NFData b)
55    ⇒ (a → Bool)       -- isTrivial
56    → (a → [a])        -- decompose problem
57    → (a → [b] → b)   -- combine solutions
58    → (a → Par b)      -- trivial algorithm
59    → a                -- problem
60    → Par b            -- result
61
62  parDivideAndConquer
63    :: Closure (Closure a → Bool)            -- is trivial
64    → Closure (Closure a → [Closure a])      -- decompose problem
65    → Closure (Closure a → [Closure b] → Closure b)  -- combine solutions
66    → Closure (Closure a → Par (Closure b)) --trivial algorithm
67    → Closure a                              -- problem
68    → Par (Closure b)                        -- result
69
70  pushDivideAndConquer
71    :: Closure (Closure a → Bool)            -- is trivial
72    → Closure (Closure a → [Closure a])      -- decompose problem
73    → Closure (Closure a → [Closure b] → Closure b) -- combine solutions
74    → Closure (Closure a → Par (Closure b)) -- trivial algorithm
75    → Closure a                              -- problem
76    → Par (Closure b)                        -- result
77
78  ------------------------
79  -- map-reduce family
80
81  parMapReduceRangeThresh
82    :: Closure Int                                          -- threshold
83    → Closure InclusiveRange                                -- range over which to calculate
84    → Closure (Closure Int → Par (Closure a))               -- compute one result
85    → Closure (Closure a → Closure a → Par (Closure a)) -- compute two results (associate)
86    → Closure a                                             -- initial value
87    → Par (Closure a)
88
89  pushMapReduceRangeThresh
```

```
90    :: Closure Int                                              -- threshold
91    → Closure InclusiveRange                                    -- range over which to calculate
92    → Closure (Closure Int → Par (Closure a))                   -- compute one result
93    → Closure (Closure a → Closure a → Par (Closure a)) -- compute two results (associate)
94    → Closure a                                                 -- initial value
95    → Par (Closure a)
```

Listing A.13: HdpH-RS Skeleton API

A.10 Using Chaos Monkey in Unit Testing

The `chaosMonkeyUnitTest` is on line 19 of Listing A.14.

```
1  -- | example use of chaos monkey unit testing with Sum Euler.
2  main = do
3      conf ← parseCmdOpts
4      chaosMonkeyUnitTest
5         conf -- user defined RTS options
6         "sumeuler-pushMapFT" -- label for test
7         759924264 -- expected value
8         (ft_push_farm_sum_totient_chunked 0 50000 500) -- Par computation to run
9                                                        -- in presence of chaos monkey
10   where
11     -- using fault tolerant explicit pushMap skeleton
12     ft_push_farm_sum_totient_chunked :: Int → Int → Int → Par Integer
13     ft_push_farm_sum_totient_chunked lower upper chunksize =
14         sum <$> FT.pushMapNF $(mkClosure [| sum_totient |]) chunked_list
15     chunked_list = chunk chunksize [upper, upper - 1 .. lower] :: [[Int]]
16
17 -- | helper function in 'Control.Parallel.HdpH' to run
18 --   a Par computation unit test with chaos monkey enabled.
19 chaosMonkeyUnitTest :: (Eq a, Show a)
20                      ⇒ RTSConf -- user defined RTS configuration
21                      → String  -- label identifier for unit test
22                      → a       -- expected value
23                      → Par a   -- Par computation to execute with failure
24                      → IO ()
25 chaosMonkeyUnitTest conf label expected f = do
26     let tests = TestList $ [runTest label expected f]
27     void $ runTestTT tests -- run HUnit test
28   where
29     runTest :: (Show a,Eq a) ⇒ String → a → Par a → Test
30     runTest label expected f =
31       let chaosMonkeyConf = conf {chaosMonkey = True, maxFish = 10 , minSched = 11}
32           test = do
33            result ← evaluate =« runParIO chaosMonkeyConf f -- run HdpH-RS computation 'f'
34            case result of
35              Nothing → assert True -- non-root nodes do not perform unit test
36              Just x → putStrLn (label++"␣result:␣"++show x) »
37                       assertEqual label x expected -- compare result vs expected value
38       in TestLabel label (TestCase test)
```

Listing A.14: Using Chaos Monkey in Unit Testing

A.11 Benchmark Implementations

A.11.1 Fibonacci

```
1  -- | sequential Fibonacci
2  fib :: Int → Integer
3  fib n | n ≤ 1    = 1
4        | otherwise = fib (n-1) + fib (n-2)
5
6  -- | lazy divide-and-conquer skeleton
7  spark_skel_fib :: Int → Int → Par Integer
8  spark_skel_fib seqThreshold n = unClosure <$> skel (toClosure n)
9    where
10     skel = parDivideAndConquer
11              $(mkClosure [| dnc_trivial_abs (seqThreshold) |])
12              $(mkClosure [| dnc_decompose |])
13              $(mkClosure [| dnc_combine |])
14              $(mkClosure [| dnc_f |])
15
16 -- | eager divide-and-conquer skeleton
17 push_skel_fib :: [NodeId] → Int → Int → Par Integer
18 push_skel_fib nodes seqThreshold n = unClosure <$> skel (toClosure n)
19   where
20     skel = pushDivideAndConquer
21              nodes
22              $(mkClosure [| dnc_trivial_abs (seqThreshold) |])
23              $(mkClosure [| dnc_decompose |])
24              $(mkClosure [| dnc_combine |])
25              $(mkClosure [| dnc_f |])
26
27 -- | fault tolerant lazy divide-and-conquer skeleton
28 ft_spark_skel_fib :: Int → Int → Par Integer
29 ft_spark_skel_fib seqThreshold n = unClosure <$> skel (toClosure n)
30   where
31     skel = FT.parDivideAndConquer
32              $(mkClosure [| dnc_trivial_abs (seqThreshold) |])
33              $(mkClosure [| dnc_decompose |])
34              $(mkClosure [| dnc_combine |])
35              $(mkClosure [| dnc_f |])
36
37 -- | fault tolerant eager divide-and-conquer skeleton
38 ft_push_skel_fib :: Int → Int → Par Integer
39 ft_push_skel_fib seqThreshold n = unClosure <$> skel (toClosure n)
40   where
41     skel = FT.pushDivideAndConquer
42              $(mkClosure [| dnc_trivial_abs (seqThreshold) |])
43              $(mkClosure [| dnc_decompose |])
44              $(mkClosure [| dnc_combine |])
45              $(mkClosure [| dnc_f |])
46
47 -- | is trivial case
48 dnc_trivial_abs :: (Int) → (Closure Int → Bool)
49 dnc_trivial_abs (seqThreshold) =
50   λ clo_n → unClosure clo_n ≤ max 1 seqThreshold
51
```

```
52 -- | decompose problem
53 dnc_decompose =
54   λ clo_n → let n = unClosure clo_n in [toClosure (n-1), toClosure (n-2)]
55
56 -- | combine solutions
57 dnc_combine =
58   λ _ clos → toClosure $ sum $ map unClosure clos
59
60 -- | trivial sequential case
61 dnc_f =
62   λ clo_n → toClosure <$> (force $ fib $ unClosure clo_n)
```

Listing A.15: Fibonacci Benchmark Implementations

A.11.2 Sum Euler

```
1  -- | sequential Euler's totient function
2  totient :: Int → Integer
3  totient n = toInteger $ length $ filter (λ k → gcd n k == 1) [1 ∘ . n]
4
5  -- | lazy parallel-map skeleton with chunking
6  chunkfarm_sum_totient :: Int → Int → Int → Par Integer
7  chunkfarm_sum_totient lower upper chunksize =
8    sum <$> parMapChunkedNF chunksize $(mkClosure [| totient |]) list
9      where
10       list = [upper, upper - 1 .. lower] :: [Int]
11
12 -- | eager parallel-map skeleton with chunking
13 chunkfarm_push_sum_totient :: Int → Int → Int → Par Integer
14 chunkfarm_push_sum_totient lower upper chunksize = do
15   nodes ← allNodes
16   sum <$> pushMapChunkedNF nodes chunksize $(mkClosure [| totient |]) list
17     where
18       list = [upper, upper - 1 .. lower] :: [Int]
19
20 -- | fault tolerant lazy parallel-map skeleton with chunking
21 ft_chunkfarm_sum_totient :: Int → Int → Int → Par Integer
22 ft_chunkfarm_sum_totient lower upper chunksize =
23   sum <$> FT.parMapChunkedNF chunksize $(mkClosure [| totient |]) list
24     where
25       list = [upper, upper - 1 .. lower] :: [Int]
26
27 -- | fault tolerant eager parallel-map skeleton with chunking
28 ft_chunkfarm_push_sum_totient :: Int → Int → Int → Par Integer
29 ft_chunkfarm_push_sum_totient lower upper chunksize =
30   sum <$> FT.pushMapChunkedNF chunksize $(mkClosure [| totient |]) list
31     where
32       list = [upper, upper - 1 .. lower] :: [Int]
```

Listing A.16: Sum Euler Benchmark Implementations

A.11.3 Summatory Liouville

```
1  -- | Liouville function
```

```
liouville :: Integer → Int
liouville n
  | n == 1 = 1
  | length (primeFactors n) `mod` 2 == 0 = 1
  | otherwise = -1

-- | Summatory Liouville function from 1 to specified Integer
summatoryLiouville :: Integer → Integer
summatoryLiouville x = sumLEvalChunk (1,x)

-- | sequential sum of Liouville values between two Integers.
sumLEvalChunk :: (Integer,Integer) → Integer
sumLEvalChunk (lower,upper) =
     let chunkSize = 1000
         smp_chunks = chunk chunkSize [lower,lower+1..upper] :: [[Integer]]
         tuples     = map (head Control.Arrow.&&& last) smp_chunks
     in sum $ map (λ(lower,upper) → sumLEvalChunk' lower upper 0) tuples

-- | accumulative Summatory Liouville helper
sumLEvalChunk' :: Integer → Integer → Integer → Integer
sumLEvalChunk' lower upper total
  | lower > upper = total
  | otherwise = let s = toInteger $ liouville lower
                in sumLEvalChunk' (lower+1) upper (total+s)

-- | lazy parallel-map skeleton with slicing
farmParSumLiouvilleSliced :: Integer → Int → Par Integer
farmParSumLiouvilleSliced x chunkSize = do
  let chunked = chunkedList x chunkSize
  sum <$> parMapSlicedNF chunkSize
          $(mkClosure [|sumLEvalChunk|])
          chunked

-- | eager parallel-map skeleton with slicing
farmPushSumLiouvilleSliced :: Integer → Int → Par Integer
farmPushSumLiouvilleSliced x chunkSize = do
  let chunked = chunkedList x chunkSize
  nodes ← allNodes
  sum <$> pushMapSlicedNF nodes chunkSize
          $(mkClosure [|sumLEvalChunk|])
          chunked

-- | fault tolerant lazy parallel-map skeleton with slicing
ft_farmParSumLiouvilleSliced :: Integer → Int → Par Integer
ft_farmParSumLiouvilleSliced x chunkSize = do
  let chunked = chunkedList x chunkSize
  sum <$> FT.parMapSlicedNF chunkSize
          $(mkClosure [|sumLEvalChunk|])
          chunked

-- | fault tolerant eager parallel-map skeleton with slicing
ft_farmPushSumLiouvilleSliced :: Integer → Int → Par Integer
ft_farmPushSumLiouvilleSliced x chunkSize = do
  let chunked = chunkedList x chunkSize
  sum <$> FT.pushMapSlicedNF chunkSize
          $(mkClosure [|sumLEvalChunk|])
```

```
58            chunked
```

Listing A.17: Summatory Liouville Benchmark Implementations

A.11.4 Queens

```
1  -- | monad-par implementation of Queens
2  monadpar_queens :: Int → Int → MonadPar.Par [[Int]]
3  monadpar_queens nq threshold = step 0 []
4    where
5      step :: Int → [Int] → MonadPar.Par [[Int]]
6      step !n b
7          | n ≥ threshold = return (iterate (gen nq) [b] !! (nq - n))
8          | otherwise = do
9             rs ← MonadPar.C.parMapM (step (n+1)) (gen nq [b])
10            return (concat rs)
11
12 -- | compute Queens solutions using accumulator
13 dist_queens = dist_queens' 0 []
14
15 -- | Porting monad-par solution to HdpH-RS
16 dist_queens' :: Int → [Int] → Int → Int → Par [[Int]]
17 dist_queens' !n b nq threshold
18   | n ≥ threshold = force $ iterate (gen nq) [b] !! (nq - n)
19   | otherwise = do
20       let n' = n+1
21       vs ← mapM (λb' → spawn
22                            $(mkClosure [| dist_queens_abs (n',b',nq,threshold) |]))
23                            (gen nq [b])
24       rs ← mapM (get) vs
25       force $ concatMap unClosure rs
26
27 -- | function closure
28 dist_queens_abs :: (Int,[Int],Int,Int) → Par (Closure [[Int]])
29 dist_queens_abs (n,b,nq,threshold) =
30   dist_queens' n b nq threshold >>= return ∘ toClosure
31
32 -- | HdpH-RS solution using threads for execution on one-node
33 dist_skel_fork_queens :: Int → Int → Par [[Int]]
34 dist_skel_fork_queens nq threshold = skel (0,nq,[])
35   where
36     skel = forkDivideAndConquer trivial decompose combine f
37     trivial (n',_,_) = n' ≥ threshold
38     decompose (n',nq',b') = map (λb'' → (n'+1,nq',b'')) (gen nq' [b'])
39     combine _ a = concat a
40     f (n',nq',b') = force (iterate (gen nq') [b'] !! (nq' - n'))
41
42 -- | compute Queens solutions using accumulator with fault tolerance
43 ft_dist_queens = ft_dist_queens' 0 []
44
45 -- | Porting monad-par solution to HdpH-RS with fault fault tolerance
46 ft_dist_queens' :: Int → [Int] → Int → Int → Par [[Int]]
47 ft_dist_queens' !n b nq threshold
48   | n ≥ threshold = force $ iterate (gen nq) [b] !! (nq - n)
49   | otherwise = do
50       let n' = n+1
```

```
51        vs ← mapM (λb' → supervisedSpawn
52                             $(mkClosure [| dist_queens_abs (n',b',nq,threshold) |]))
53                             (gen nq [b])
54        rs ← mapM (get) vs
55        force $ concatMap unClosure rs
56
57  -- | function closure
58  ft_dist_queens_abs :: (Int,[Int],Int,Int) → Par (Closure [[Int]])
59  ft_dist_queens_abs (n,b,nq,threshold) =
60    ft_dist_queens' n b nq threshold >>= return ∘ toClosure
61
62  -- | lazy divide-and-conquer skeleton
63  dist_skel_par_queens :: Int → Int → Par [[Int]]
64  dist_skel_par_queens nq threshold = unClosure <$> skel (toClosure (0,nq,[]))
65    where
66      skel = parDivideAndConquer
67               $(mkClosure [| dnc_trivial_abs (threshold) |])
68               $(mkClosure [| dnc_decompose |])
69               $(mkClosure [| dnc_combine |])
70               $(mkClosure [| dnc_f |])
71
72  -- | eager divide-and-conquer skeleton
73  dist_skel_push_queens :: Int → Int → Par [[Int]]
74  dist_skel_push_queens nq threshold = unClosure <$> skel (toClosure (0,nq,[]))
75    where
76      skel x_clo = do
77              nodes ← allNodes
78              pushDivideAndConquer
79               nodes
80               $(mkClosure [| dnc_trivial_abs (threshold) |])
81               $(mkClosure [| dnc_decompose |])
82               $(mkClosure [| dnc_combine |])
83               $(mkClosure [| dnc_f |])
84               x_clo
85
86  -- | fault tolerant lazy divide-and-conquer skeleton
87  ft_dist_skel_par_queens :: Int → Int → Par [[Int]]
88  ft_dist_skel_par_queens nq threshold = unClosure <$> skel (toClosure (0,nq,[]))
89    where
90      skel = FT.parDivideAndConquer
91               $(mkClosure [| dnc_trivial_abs (threshold) |])
92               $(mkClosure [| dnc_decompose |])
93               $(mkClosure [| dnc_combine |])
94               $(mkClosure [| dnc_f |])
95
96  -- | fault tolerance eager divide-and-conquer skeleton
97  ft_dist_skel_push_queens :: Int → Int → Par [[Int]]
98  ft_dist_skel_push_queens nq threshold = unClosure <$> skel (toClosure (0,nq,[]))
99    where
100     skel = FT.pushDivideAndConquer
101              $(mkClosure [| dnc_trivial_abs (threshold) |])
102              $(mkClosure [| dnc_decompose |])
103              $(mkClosure [| dnc_combine |])
104              $(mkClosure [| dnc_f |])
105
106 -- | is trivial case
107 dnc_trivial_abs :: (Int) → (Closure  (Int,Int,[Int]) → Bool)
```

```
dnc_trivial_abs threshold =
  λ clo_n → let (!n,_nq,_b) = unClosure clo_n in n ≥ threshold

-- | decompose problem
dnc_decompose :: Closure (Int, Int, [Int]) → [Closure (Int, Int, [Int])]
dnc_decompose =
  λ clo_n → let (n,nq,b) = unClosure clo_n
            in map (λb' → toClosure (n+1,nq,b')) (gen nq [b])

-- | combine solutions
dnc_combine ::  a → [Closure [[Int]]] → Closure [[Int]]
dnc_combine =
  λ _ clos → toClosure $ concatMap unClosure clos

-- | trivial sequential case
dnc_f :: Closure (Int, Int, [Int]) → Par (Closure [[Int]])
dnc_f =
  λ clo_n → do
       let (n,nq,b) = unClosure clo_n
       toClosure <$> force (iterate (gen nq) [b] !! (nq - n))
```

Listing A.18: Queens Benchmark Implementations

A.11.5 Mandelbrot

```
-- | sequential implementation of Mandelbrot
mandel :: Int → Complex Double → Int
mandel max_depth c = loop 0 0
  where
   fn = magnitude
   loop i !z
    | i == max_depth = i
    | fn(z) ≥ 2.0   = i
    | otherwise      = loop (i+1) (z*z + c)

-- | lazy map-reduce skeleton
runMandelPar
  :: Double → Double → Double → Double → Int → Int → Int → Int → Par VecTree
runMandelPar minX minY maxX maxY winX winY maxDepth threshold =
    unClosure <$> skel (toClosure (Leaf V.empty))
  where
    skel = parMapReduceRangeThresh
            (toClosure threshold)
            (toClosure (InclusiveRange 0 (winY-1)))
            $(mkClosure [| map_f (minX,minY,maxX,maxY,winX,winY,maxDepth) |])
            $(mkClosure [| reduce_f |])

-- | eager map-reduce skeleton
runMandelPush
  :: Double → Double → Double → Double → Int → Int → Int → Int → Par VecTree
runMandelPush minX minY maxX maxY winX winY maxDepth threshold =
    unClosure <$> skel (toClosure (Leaf V.empty))
  where
    skel = pushMapReduceRangeThresh
            (toClosure threshold)
            (toClosure (InclusiveRange 0 (winY-1)))
```

```
32              $(mkClosure [| map_f (minX,minY,maxX,maxY,winX,winY,maxDepth) |])
33              $(mkClosure [| reduce_f |])
34
35  -- | fault tolerant lazy map-reduce skeleton
36  runMandelParFT
37    :: Double → Double → Double → Double → Int → Int → Int → Int → Par VecTree
38  runMandelParFT minX minY maxX maxY winX winY maxDepth threshold =
39      unClosure <$> skel (toClosure (Leaf V.empty))
40    where
41      skel = FT.parMapReduceRangeThresh
42              (toClosure threshold)
43              (toClosure (FT.InclusiveRange 0 (winY-1)))
44              $(mkClosure [| map_f (minX,minY,maxX,maxY,winX,winY,maxDepth) |])
45              $(mkClosure [| reduce_f |])
46
47  -- | eager map-reduce skeleton
48  runMandelPushFT
49    :: Double → Double → Double → Double → Int → Int → Int → Int → Par VecTree
50  runMandelPushFT minX minY maxX maxY winX winY maxDepth threshold =
51      unClosure <$> skel (toClosure (Leaf V.empty))
52    where
53      skel = FT.pushMapReduceRangeThresh
54              (toClosure threshold)
55              (toClosure (FT.InclusiveRange 0 (winY-1)))
56              $(mkClosure [| map_f (minX,minY,maxX,maxY,winX,winY,maxDepth) |])
57              $(mkClosure [| reduce_f |])
58
59  ------------------------------------------------
60  -- Map and Reduce function closure implementations
61
62  -- | implementation of map function
63  map_f :: (Double,Double,Double,Double,Int,Int,Int)
64        → Closure Int
65        → Par (Closure VecTree)
66  map_f (minX,minY,maxX,maxY,winX,winY,maxDepth) = λy_clo → do
67      let y = unClosure y_clo
68      let vec = V.generate winX (λx → mandelStep y x)
69      seq (vec V.! 0) $ return (toClosure (Leaf vec))
70    where
71      mandelStep i j = mandel maxDepth (calcZ i j)
72      calcZ i j = ((fromIntegral j * r_scale) / fromIntegral winY + minY) :+
73             ((fromIntegral i * c_scale) / fromIntegral winX + minX)
74      r_scale =  maxY - minY  :: Double
75      c_scale =   maxX - minX  :: Double
76
77  -- | implementation of reduce function
78  reduce_f :: Closure VecTree → Closure VecTree → Par (Closure VecTree)
79  reduce_f = λa_clo b_clo → return $ toClosure (MkNode (unClosure a_clo) (unClosure b_clo))
```

Listing A.19: Mandelbrot Benchmark Implementations